Salinity and modelling of the Annaba aquifer system, North-East of Algeria

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Abstract

The potentiometer area in the Annaba basin, covering an area of 264 km^2, has declined considerably since 1995. The analysis of the chronological hydrographs (1991–2009) of the piezometric observations shows that this decline is related to about twenty years (20 years) drought that began in 1991. To synthesize hydrological data and study regional changes in aquifer interactions caused by changes in discharge, and determine the contamination of aquifers by salty intrusion in coastal areas, and making forecasts by the year 2023, a multi-layered transient model as well as a solute transport model has been developed. The groundwater flow was modelled using the finite difference method with a horizontal dimension of 500 × 500 m for the cells. The model consists of two layers, the first corresponding to the alluvial phreatic aquifer and the second to the deep confined aquifer, and is calibrated against the steady state groundwater heads recorded before 1996. Model verification was done by history matching over the period 1991–2009. Under steady-state conditions, the correspondence between simulated and observed water levels is generally good (average difference of 0.4 m). For the deep aquifer, the simulated time-series hydrographs closely match the recorded hydrographs for most of the observation wells. For the alluvial aquifer, the recorded hydrographs cover only a short time period, but they are reproduced. The model indicates that groundwater pumping induced a decrease in natural discharge, a downward leakage in most of the basin and a continual water-level decline. The model has also been applied to the analysis of recharge impact. Simulating the behaviour of the system over the period 1991–2009 without pumping indicated small changes in hydraulic head.

These results show that the groundwater reservoir has a low recharge, but excellent hydraulic properties. A solute-transport model was used to study aquifer contamination from salty intrusion in coastal sectors; it was extended to the year 2023 by simulating an optimistic hypothesis that maintains present pumping until 2023. The model indicates that the head decrease of the alluvial phreatic and deep confined aquifers will be 4 m and 5 m respectively. The solute concentration in the deep confined aquifer will increase from 1 g·dm^{-3} (prior 2009) to 5 g·dm^{-3} in 2023.

Key words: *Annaba, contamination, North-East of Algeria, salinity, solute-transport model*

INTRODUCTION AND OBJECTIVES

The Annaba coastal aquifer is the only natural source of water supply in the Annaba region. Water is presently accessed through pumping of more than 100 wells, with a total estimated annual production in 2001 of about 20 million cubic meters [DJABRI et al. 2010; HANI et al. 2003]. Current rates of aquifer abstraction are excessive [LAMOUROUX, HANI 2006] and deterioration of groundwater quality is documented in many parts of the Annaba region.

In the present study, the collected basic data are used for the preparation of the groundwater flow and mass transport model for quantitative assessment of the impact of contaminant migration in the watershed. Indeed, the first entry in the system is rainfall. The effective rainfall was calculated with monthly precipitation using the Thornthwaite formula. For the numerical code of flow, it is necessary to introduce the geometrical characteristics of each of the three horizons. The coasts of the ground surface and bottom of the three horizons were determined essentially from the data analysis of drilling and expressed in relation to general levelling (NGA). The introduction of the permeability values of each layer is also essential. Transmissivity values resulting from the pumping of test carried out on NSAS while referring to granulometry and thickness of the alluvium or of transmissivity kriging (NG) are divided by the thickness of the horizon considered before being introduced into model. The flows of the Seybouse and Ressoulwadis are determined from the gauging carried out by the ANRH upstream of the plain.

In this study, a model of transport mass Modpath [POLLOCK 1989] is used to determine the evolution of deep water salinity by the 2030 deadline. The Modpath model calibration was performed on the results of chloride analyses obtained in 2002 for which we have 85 values of chloride on the deep gravel aquifer and about thirty on the surface aquifer.

The Annaba coastal aquifer is the only natural source of water supply in the Annaba region. Water is presently accessed through pumping of more than 100 wells [DJABRI et al. 2010; HANI et al. 2003]. Current rates of aquifer abstraction are dramatic, and deterioration of groundwater quality is documented in many parts of the Annaba region. In this study, we tried using hydrodynamic model to know the present state of the resource and evaluate the anthropic effects on the environment.

STUDY AREA

The studied area is situated in the extreme North Eastern of Algeria. It limited to the North by the Mediterranean Sea, to the west by the metamorphic Edough complex. It is limited to the South by the Fetzara Lake and the Numidian chain of Cheffia mounts (Fig. 1). The aquifer system is composed of Mio-Pliocene and Quaternary sediments of Ben-Ahmed and Ben-M'hidi trench.

The filling sediments of these two grabens are heterogeneous, they comprise an alternation of sandy clays, sands and gravels where two main aquifers of unequal importance are distinguish (Fig. 2):
– the superficial aquifer which extends over the whole plain of Annaba and flows through the superficial silts,
– the gravel aquifer which covers the entire area of study and shows good hydraulic characteristics.

These two horizons are separated by an intermediate level of semi-permeable and/or impermeable layer. They constitute a single complex aquifer [BOUGHERIRA et al. 2014; DJABRI et al. 2010; HANI et al. 2003].

In this study, we are interested in hydrodynamic behaviour and hydrodispersive of the Ben-Ahmed graben.

MATERIAL AND METHODS

Many semi-annual surveys of the piezometric level and geochemical analysis have been monitored from 2012 to 2015. The analyses are carried out on a network of 60 wells in the lower Seybouse basin. Some sampled wells are used by the neighbouring population
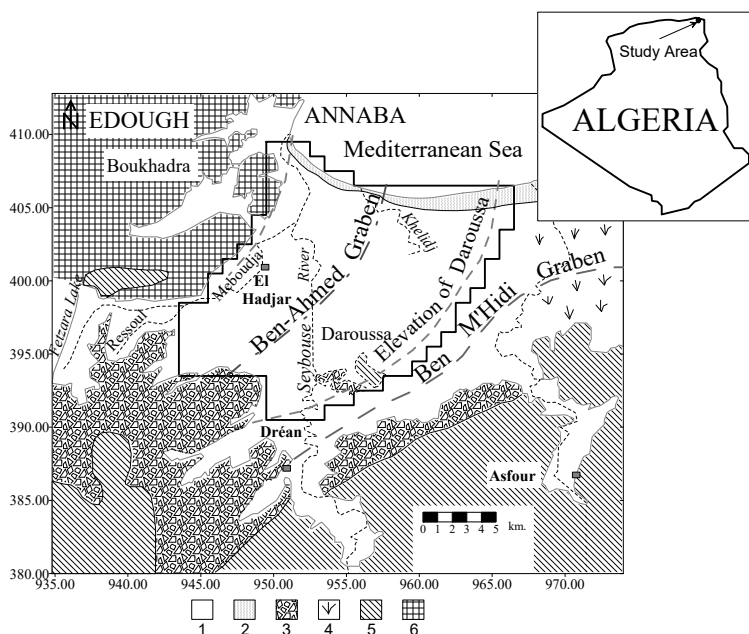

Fig. 1. Location map of study area; *1* = undifferentiated Quaternary, *2* = sandstone of dune, *3* = ancient alluvium, *4* = marshes, *5* = Numidian sandstone or clay, *6* = metamorphic formation; source: own elaboration
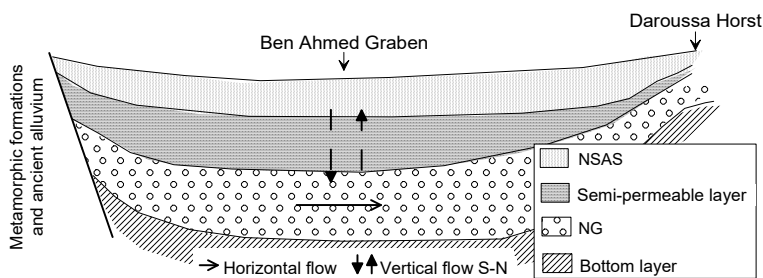

Fig. 2. Cross-section through the Ben-Ahmed Graben;
source: own elaboration

for daily drinking, irrigation and animal alimentation.

Generally, the pumping tests allowed to estimate the hydrodynamic parameters of the aquifer system. In fact, the mean transmissivities of the surface horizon vary from $2 \cdot 10^{-6}$ to $8 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$. The conductivity oscillates between $4 \cdot 10^{-7}$ and $1.6 \cdot 10^{-5}$ $m \cdot s^{-1}$ [BOUGHERIRA *et al.* 2015].

The semi-permeable, intermediate layer, is characterized by conductivities varying between 10^{-8} and 10^{-7} $m \cdot s^{-1}$. The gravel layer is characterized by transmissivities of $1.0 \cdot 10^{-3}$ and $4.5 \cdot 10^{-2}$ $m^2 \cdot s^{-1}$ and the conductivity is also important with values varying between $1 \cdot 10^{-4}$ and $5.5 \cdot 10^{-4}$ $m \cdot s^{-1}$.

In the present study, groundwater monitoring has been taken up for effective assessment through understanding of hydrogeology, geology and water-chemistry of the watershed. The collected basic data is used for the preparation of the groundwater flow and mass transport model for quantitative assessment of impact of anthropical influence on contaminant migration in the watershed [BOUGHERIRA *et al.* 2014].

RESULTS AND DISCUSSION

Earlier studies in this area have shown the following observations [HANI *et al.* 2003]. The decrease of water levels, due the intensive use of groundwater near the coast, creates piezometric depressions and the extension of zero level towards the South. Such situation is accentuated by the weakness of inputs (Fig. 3).

The dip of the gravel strata is mainly towards the sea (Fig. 4). The geometrical characteristics (thickness and dip changes) of gravel layer show that aquifer would emerge to the sea on a few kilometres (about 4–5 km) from the coast [DJABRI *et al.* 2010; HANI *et al.* 2006; LAMOUROUX, HANI 2006].

On the coastline of the Ben-Ahmed Graben, the gravel aquifer is characterised by a high conductivity, these high values are observed in the southern and northern parts of the aquifer. In order to determine the origin of this salinity, sampling campaigns were conducted in 2012 and 2015. The variables observed only in two profiles perpendicular to the sea are: chlorides, sodium, conductivity and strontium. The results display the existence of two origins.

The first one in the southern part, in relation with the existence of evaporites, where it is characterised by the increase of the Na^+, Cl^- and conductivity. The increase of strontium values, in this part, can translate the influence of evaporitic formations on the physico-chemical contents of water [DEBIÈCHE *et al.* 2003; DJABRI *et al.* 2010; HANI *et al.* 2006; LAMOUROUX, HANI 2006; VILA 1980].

The second one in the northern part, with the influence of a marine salinity, induce an increase of the Na^+, Cl^- contents and conductivity. The steady decrease of hydrochemical features from the sea to the continent on about 15 km (Fig. 5).

Such parameter variations seem to indicate a competition between sea and salt deposits influence.

A transient multilayer model to synthesise the hydrologic data and study the regional changes in aquifer interactions caused by changes in discharge.

The groundwater flow was modelled using the finite difference method with a horizontal dimension of 500×500 m for cells (Fig. 6). The model consists of two layers, the first corresponding to the alluvial phreatic aquifer and the second to the deep confined aquifer, and is calibrated against the steady state groundwater heads recorded before 1996. Model verification was done by history matching over the period 1991–2009. The figure represents the mesh and boundaries conditions use by Modflow [BOUGHERIRA *et al.* 2015; MCDONALD, HARBAUGH 1988; ZHENG, 1990] of the two aquifers [AOUN-SEBAITI *et al.* 2014; CHOUCHANE *et al.* 2014]:
a) the superficial aquifers (SA),
b) and the gravel aquifer (GA).

Under steady-state conditions (Fig. 7), the correspondence between simulated and observed water levels is generally good (average difference of 0.4 m).

Under transient state, the model indicates that groundwater pumping induced a continual water-level decline.
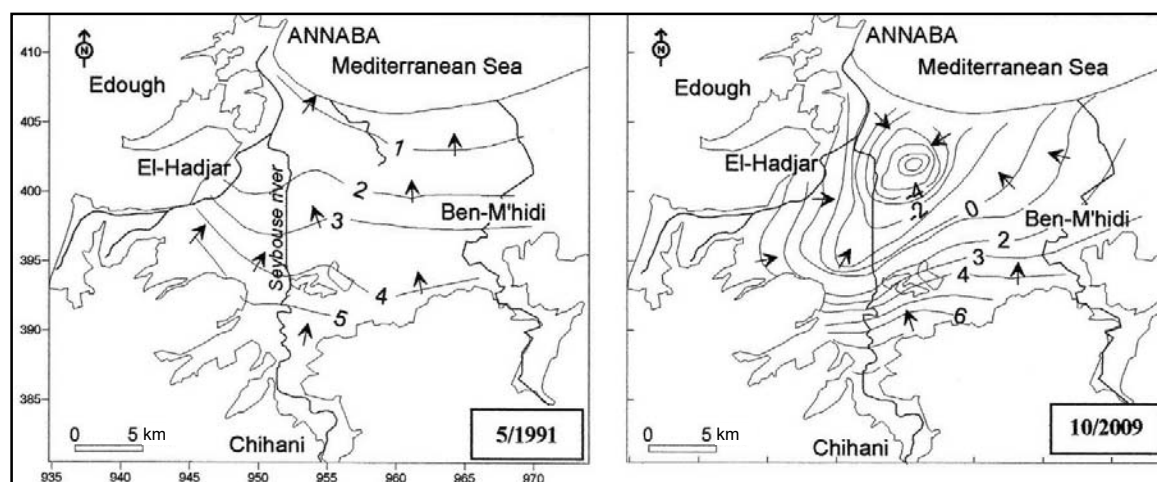

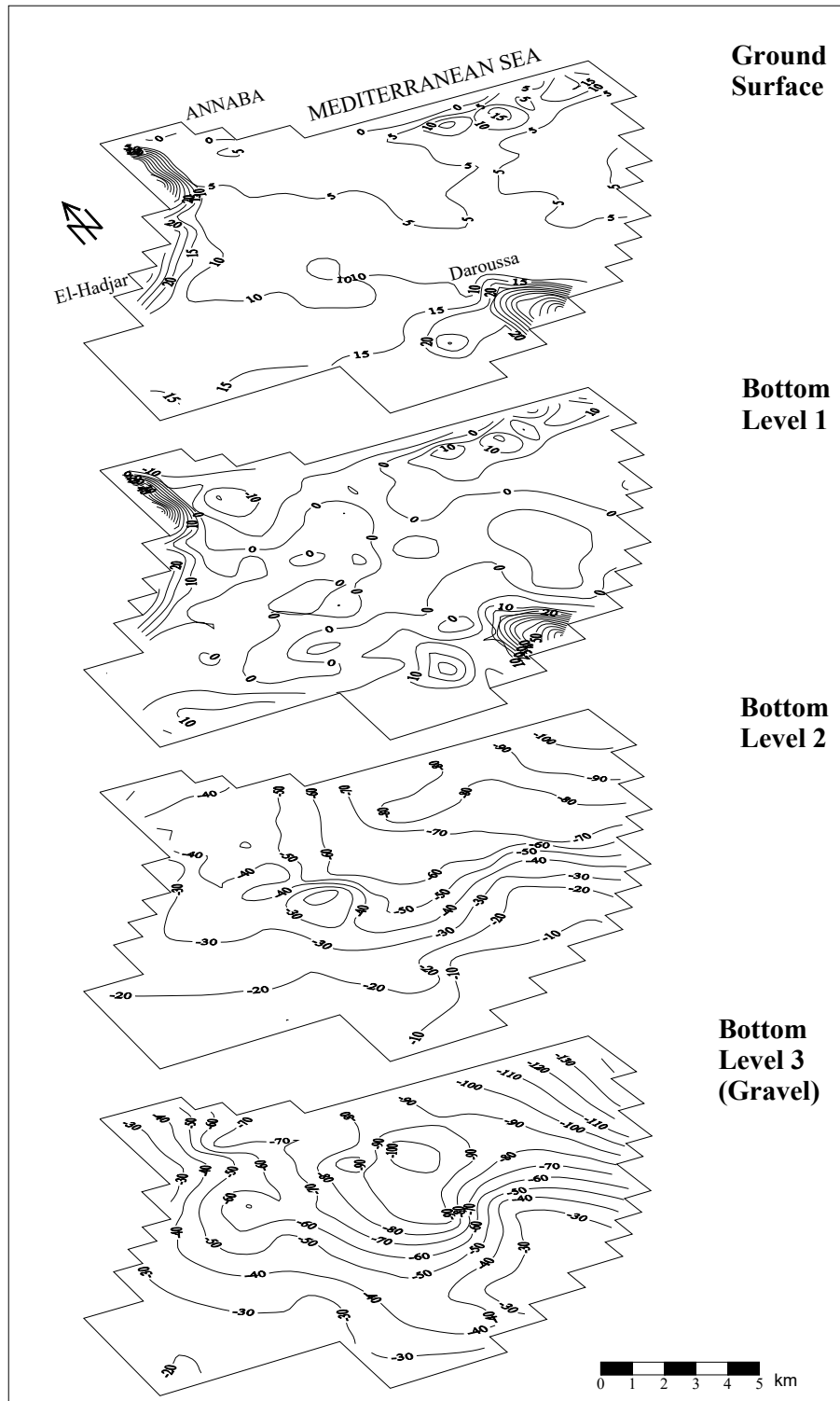Fig. 3. Variation of piezometric levels between 1991 and 2009; source: own study

Fig. 4. Geometrical characteristics of gravel layer; source: own study

The used model is to simulate the natural state over the period 1991–2009 in order to apprehend the behaviour of the system against the variability of water supplies. During this period, the output water volume is supposed to be zero. All the meshes of the model show a decrease of around 0.7 m for the two aquifers from 1991 to 2000 (Fig. 8). From 2000 to 2004, water levels tend to increase from 1 to 1.3 m in SA and 0.5 to 0.9 m in GA. A tendency to a decrease re-

starts from 2004, followed by increase of amplitude (from 0.6 m in SA and 0.4 m in GA).

This confirms that the decrease of piezometric levels cannot be related wholly to the intensive pumping, but the dryness over the last decades contributes also to the observations mentioned above.

The comparison between water budgets from 1996 to 2009: the intensive exploitation of the GA caused:
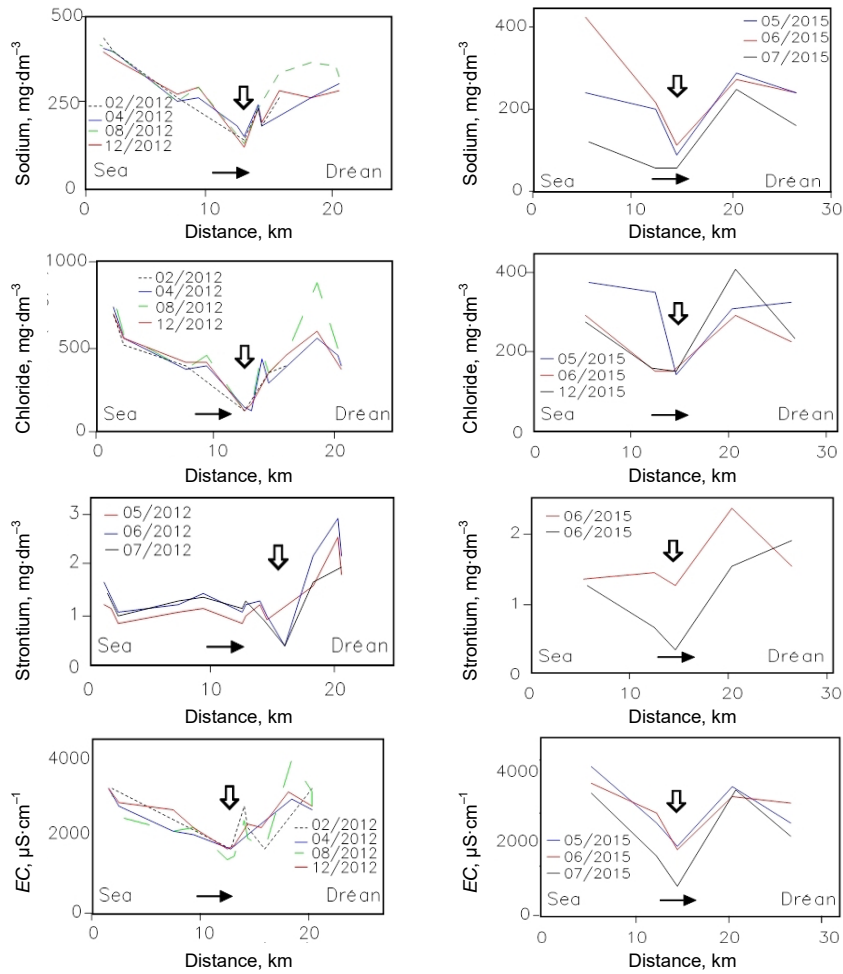
Fig. 5. Graphs for chlorides, sodium, strontium and electric conductivity (*EC*) from the sea to Drean; source: own study
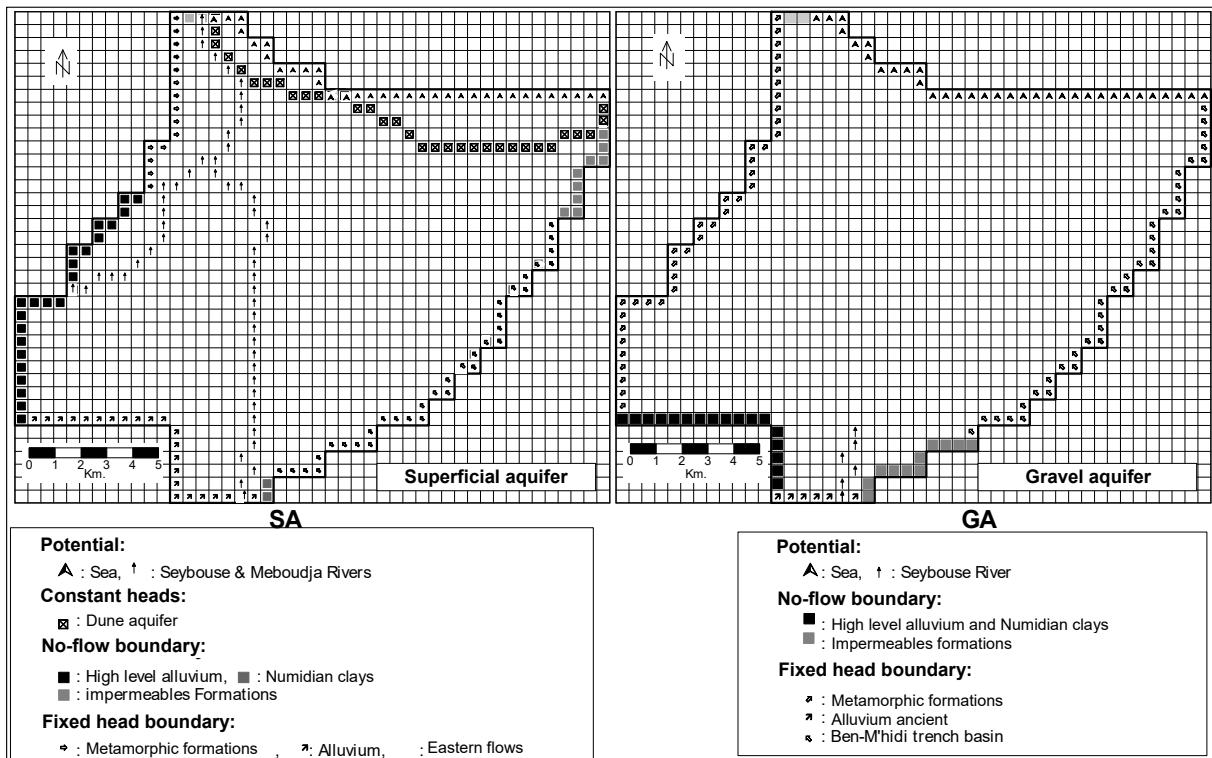

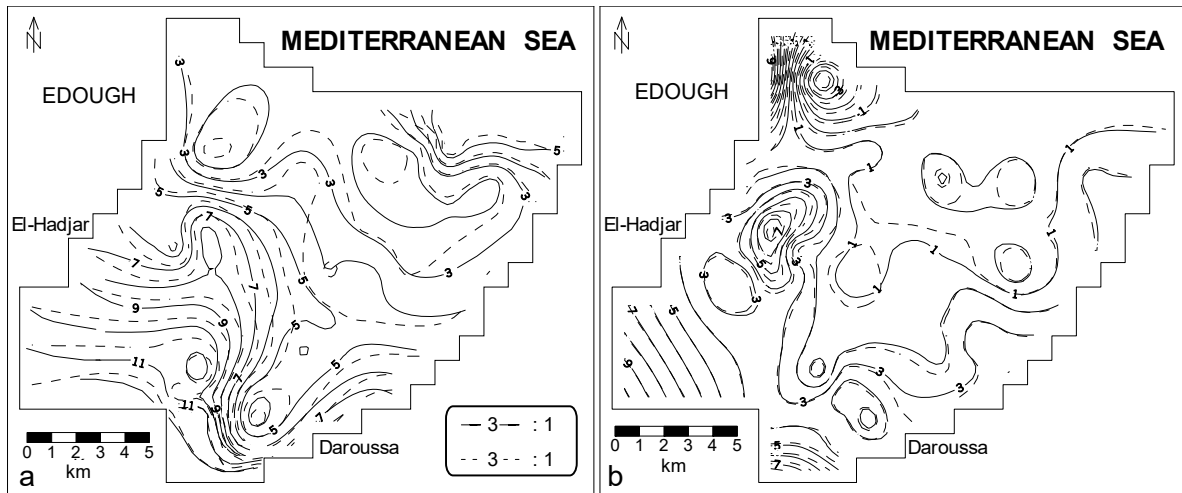Fig. 6. Cells and boundary conditions used by Modflow; source: own study

Fig. 7. Piezometric map of aquifers under steady-state; a) superficial aquifer, b) gravel aquifer. *1* = observed lines,
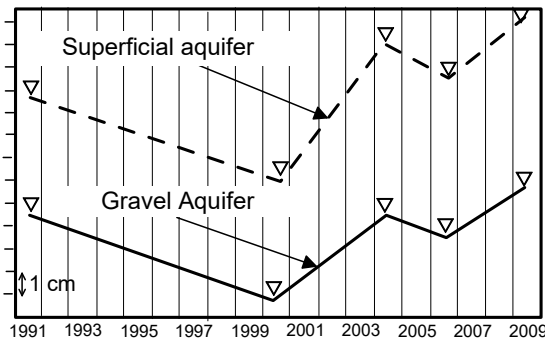*2* = simulated lines; source: own study

Fig. 8. Simulation of the natural state; source: own study

- recovery of a great amount of natural outflow,
- a relatively important contribution of the reserves,
- a decrease of about 8 m in GA,
- a hydraulic exchange variation between the two aquifers:
  - first, the leakage towards the GA, in the South (recharge zone) equilibrates with the leakage towards the SA in the North (discharge zone),

- however, in 2009, the leakage is mainly downwards, thus, showing the contribution of the SA to the whole plain.

How would be the consequences on the aquifer if the actual situation stands still? To answer this question, a solute-transport model [DOMENICO, SCHWARTZ 1990; GURUNADHA *et al.* 2001; NEUMAN 1990; PANAGOULIA, DIMOU 1996; POLLOCK 1989] was used to study aquifer contamination from salty intrusion in coastal sectors; it was extended to the year 2030 by simulating an optimistic hypothesis that maintains present pumping until 2030. The model indicates that the head decrease of the alluvial phreatic and deep confined aquifers will be 4 m and 5 m respectively (Fig. 9).

The simulated piezometric distribution illustrates the vulnerability of the aquifer in coastal sectors where flows with an important concentration of chloride may be observed, mainly towards the Salines wells field. The solute concentration in the deep confined aquifer will increase from 1 g·dm^{-3} (prior to 2009) to 5 g·dm^{-3} in 2030 (Fig. 10).
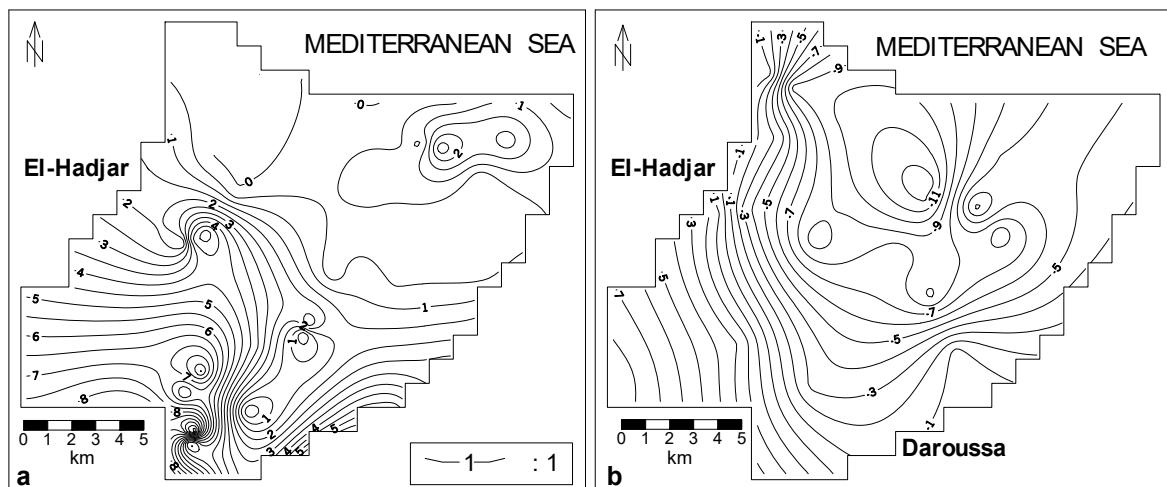

Fig. 9. Computer model prediction of the heads in 2010: a) superficial aquifer, b) gravel aquifer; *1* = simulated lines;
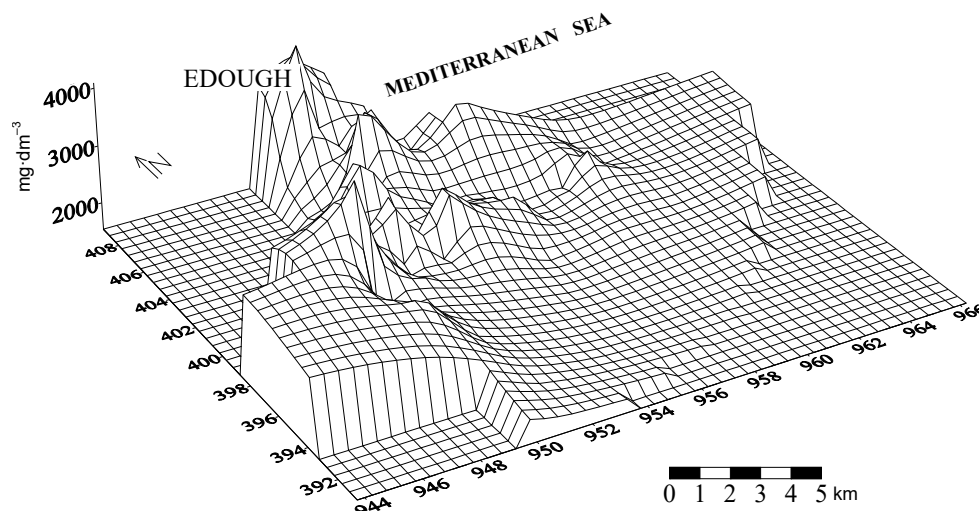source: own study

Fig. 10. Computer model prediction of the salinity in 2030; source: own study

CONCLUSIONS

Generally, the geometrical characteristics of gravel layer show that aquifer would emerge to the sea on a few kilometres (about 4–5 km) from the coast.

The decrease of water levels, due the intensive use of groundwater near the coast, creates piezometric depressions and the extension of zero level towards the south. Such situation is accentuated by the weakness of rainfalls.

The graphs for chlorides, sodium, strontium and electrical conductivity from the sea to Drean, in southern part show a significant fall of the values. In the sector near the sea, the chloride, sodium and electrical conductivity decreases significantly. Towards the South, the values of these elements increase again to very higher values. The increase of strontium values, in this part, can translate the influence of evaporitic formations on the physico-chemical contents of water. Such parameter variations seem to indicate a competition between sea and salt deposits influence.

A model is used to simulate the natural state over the period 1991–2009 in order to apprehend the behaviour of the system against the variability of water supplies. During this period, the output water volume is supposed to be zero. The results of the modeling confirm that the decrease in piezometric levels can not be entirely related to intensive pumping, but the drought in recent decades also contributes to the above-mentioned observations. The intensive exploitation of the gravel aquifer caused:
– a recovery of a great amount of natural outflow,
– a relatively important contribution of the reserves,
– a hydraulic exchange variation between the two aquifers.

The solute-transport model indicates that the head decrease of the alluvial phreatic and deep confined aquifers will be 4 m and 5 m respectively. The simulated piezometric distribution illustrates the vulnerability of the aquifer in coastal sectors where flows with an important concentration of chloride may be observed, mainly towards the Salines wells field. The solute concentration in the deep confined aquifer will increase from 1 g·dm^{-3} (prior to 2009) to 5 g·dm^{-3} in 2030.

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Zasolenie i modelowanie systemu wodonośnego Annaby w północnowschodniej Algierii

STRESZCZENIE

Objęty pomiarami obszar basenu Annaba o powierzchni 264 km^2 zmniejszył się znacząco od roku 1995. W wyniku analizy chronologicznych hydrogramów (1991–2009) z obserwacji piezometrycznych wykazała, że za to zmniejszenie odpowiada dwudziestoletnia susza, która rozpoczęła się w 1991 r. Aby dokonać syntezy danych hydrologicznych, zbadać regionalne zmiany poziomów wodonośnych wywołane zmianami w odpływie, ustalić zanieczyszczenie tych poziomów przez napływ zasolonych wód z wybrzeża i prognozować sytuację do 2023 r., zbudowano wielowarstwowy model przejściowy i model transportu substancji rozpuszczonych. Przepływ wód podziemnych modelowano metodą różnic skończonych, stosując horyzontalne komórki o wymiarach 500 × 500 m. Model składał się z dwóch warstw – pierwsza odpowiadała aluwialnemu poziomowi freatycznemu, a druga – głębokiemu poziomowi o napiętym zwierciadle wody i został skalibrowany względem ustalonego poziomu piezometrycznego notowanego przed 1996 r. Model był weryfikowany dopasowaniem historycznym dla okresu 1991–2009. Dla ustalonych warunków zależność między symulowanym a obserwowanym poziomem wody była dobra (średnia różnica 0,4 m). Dla głębokich poziomów wodonośnych symulowane serie hydrogramów były w większości studzienek obserwacyjnych ściśle dopasowane do hydrogramów z pomiarów. W poziomach aluwialnych hydrogramy z pomiarów obejmowały jedynie krótki okres, ale były powtarzalne. Model wskazuje, że pompowanie wód podziemnych powodowało zmniejszenie naturalnego odpływu i przesiąkania wgłębnego w większości obszaru oraz stały spadek poziomu wody. Model wykorzystano również do analizy wpływu zasilania. Symulowanie zachowania systemu w okresie 1991–2009 bez pompowania wykazało niewielkie zmiany wysokości hydraulicznej.

Uzyskane wyniki świadczą, że podziemny zbiornik ma niewielkie zasilanie, ale znakomite właściwości hydrauliczne. Model transportu substancji rozpuszczonych użyty do badań zanieczyszczenia poziomów wodonośnych przez solne intruzje z wybrzeża rozszerzono do 2023 r. z optymistycznym założeniem utrzymania aktualnego poziomu pompowania wody. W wyniku modelowania stwierdzono, że spadek wysokości hydraulicznej aluwialnego poziomu freatycznego i głębokiego poziomu o napiętym zwierciadle wody wyniesie odpowiednio 4 i 5 m. Stężenie substancji rozpuszczonych w głębokim poziomie wodonośnym wzrośnie od 1 g·dm^{-3} sprzed 2009 r. do 5 g·dm^{-3} w 2023 r.

Słowa kluczowe: *Annaba, model transportu substancji rozpuszczonych, północnowschodnia Algieria, zanieczyszczenie, zasolenie*