Environmental Earth Sciences (2019) 78:22
https://doi.org/10.1007/s12665-018-8005-2

THEMATIC ISSUE

Application of the GALDIT method combined with geostatistics at the Bouteldja aquifer (Algeria)

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Received: 27 May 2018 / Accepted: 17 December 2018

Abstract

This paper aims to spatially characterize the marine intrusion in the case of the Bouteldja main aquifer using the GALDIT method coupled with a geostatistical approach. The latter was used to compensate the weakness of GALDIT method for not considering the spatial variability of the studied variables. Using a field data set of the Bouteldja aquifer, the semi-variograms of four continuous important variables (hydraulic conductivity *A*, groundwater level *L*, thickness *T* and sea water intrusion *I*) were studied and modeled. The obtained structures were mainly composed of spherical models with a small nugget effect, except the *I* variable which has shown a perfectly continuous Gaussian model with zero nugget effect, arguing that the marine intrusion is seriously present and continuous. These individual results were also mapped by kriging and the intrusion easily shown on the field. However, the GALDIT computation and mapping did not confirm the found intrusion. It has merely shown a medium to low vulnerability in narrow and parallel bands close to the shore area. This work has shown that the GALDIT method used solely, without a geostatistical approach, would lead to a misinterpretation of the vulnerability of a main aquifer to saline intrusion.

Keywords GALDIT · Shore aquifer · Bouteldja · Vulnerability · Sea water intrusion · Pollution · Salinity

Introduction

Water supply has become a growingly crucial problem for big cities over the world. Decision-makers are forced to diversify water sources and resolve serious problems such as saline intrusion in the littoral aquifers. Even if the saline intrusion threat concerns only littoral cities, it remains a serious danger as many cities and mega towns in the world are on the shoreline. This is the case of Annaba mega city (Eastern Algeria) exploiting the Bouteldja littoral aquifer.

Scientists working on the problem have noticed that Annaba's population is expected to reach 2 million inhabitants by the year 2020. This will certainly worsen the condition of the Bouteldja water supply, already precarious. Moreover, current withdrawals are very far from satisfying the demand in terms of quantity and quality. They are estimated at only 100 l/i/day (liters per inhabitant, per day) compared to the 150 l/i/day recommended by World Health Organization (2004) and Aichouri (2016).

The salt water pollution of the aquifer groundwater of the sand ridge of Bouteldja by marine intrusion has been subject to many research studies (Toubal 1998; Djabri et al. 2003; Hani et al. 2003; Assassi et al. 2004; Sebaïti 2010; Bourbia 2011; Aichouri 2016; Bounab et al. 2017). They have pointed out the existence of this phenomenon by diverse multidisciplinary and methodological approaches (hydrodynamic, geophysical, chemical, and so on).

Ahcene Benamghar: Invited co-authorship.

This article is part of a Topical Collection in Environmental Earth Sciences on Groundwater resources in a changing environment, guest edited by Okke Batelaan, Fabien Magri, and Martin Sauter.

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Published online: 02 January 2019

In this respect, Sebaïti mathematical model developed in 2010, based on the simulation of underground flow between 1982 and 2005, highlighted dramatic fall of the piezometric levels in the gravel groundwater. Samples volumes have been raised from 12 to 23×10^6 m^3/year in 14 years, which generated sea water intrusion by changing the direction of the flow.

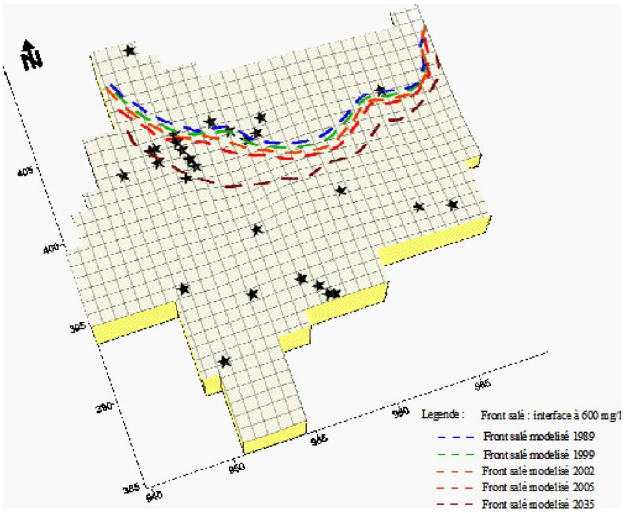

Fig. 1 Forecasts of the marine intrusion for the year 2035 (Aichouri 2016)

Also, Aichouri research in 2016 (Aichouri 2016) using marine intrusion simulation, by the year 2035, has shown that the hydrodynamic imbalance would continue permanently beyond 2005, assuming that the pumping rates as well as charging remain the same 2005 and keep going on. Furthermore, the author found out that the dispersal area would spread into the surrounding lands, about 200–300 m in the east of the plain area, 500 m in the center and could reach 1500 m in the west, compared with the year 2005 calculated position (Fig. 1).

For the south and center plain drilling, the model shows that the exploitation of underground water at its current level can be sustained without significant degradation of the water salinity (Fig. 2).

Drilling that is located further north of the plain and those located a few kilometers from the coast seem to significantly destabilize the freshwater–brackish water balance from year to year.

According to the results of the 1989 hydro-dispersive model, only a few boreholes in the northern plain were affected by Cl concentrations ranging from 500 to 800 mg/l, whereas in 2005 these same holes reached a concentration of Cl varying between 800 and 1100 mg/l (Table 1).

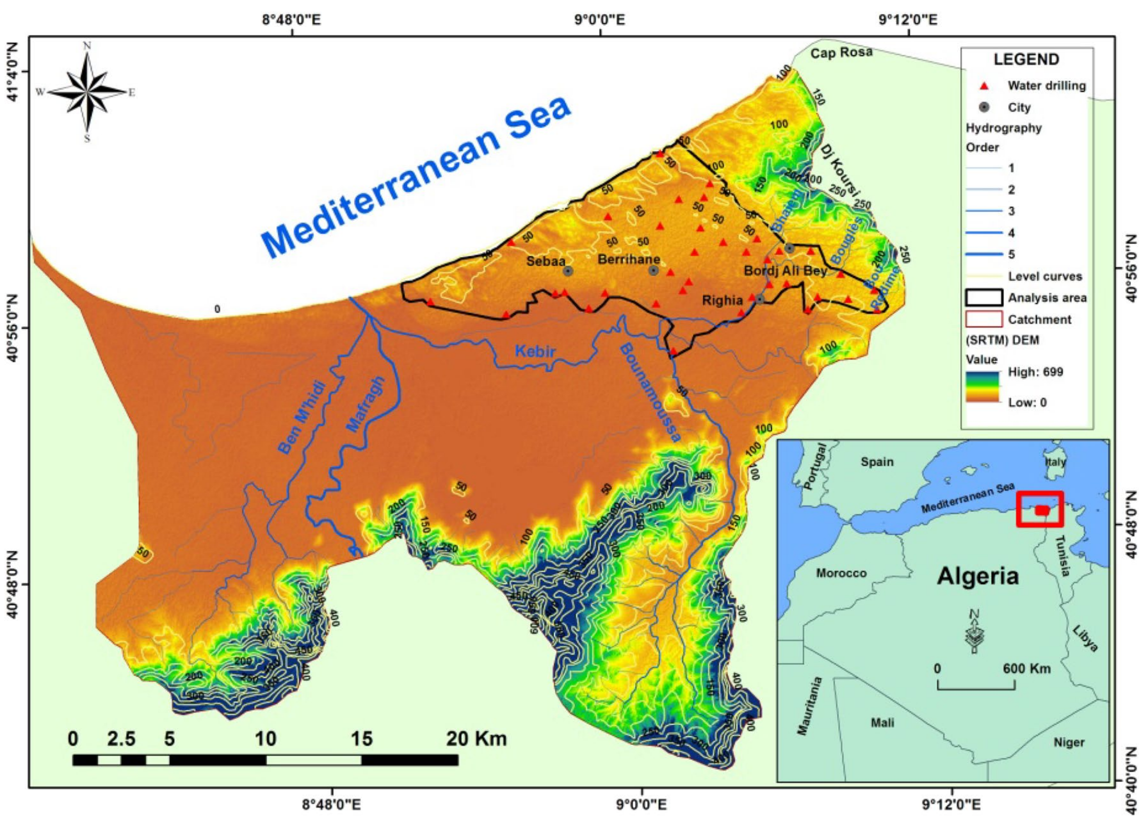

Fig. 2 Geographic situation of the sand ridge of Bouteldja (map of the study zone area)

Table 1 Assessment of the inflow and outflow of the aquifer for the years 1989, 1999, 2002 and 2005 (Aichouri 2016)

Years	Inflows (m^3/day)				Outflows (m^3/day)		
	By the limits	Recharge	Intrusion	Total	Pumping	Seaward	Total
1989	55,510	0.13	5475.20	60,985	7034.30	293.85	60,985
1999	58,767	0.08	8118.00	66,885	53,657.00	0.00	66,885
2002	54,821	0.08	9917.90	64,739	53,657.00	0.00	64,739
2005	54,795	0.13	9810.90	62,512	53,657.00	0.00	62,512

Results of the 3D hydro-dispersive model indicate that contributions due to the marine intrusion represent, respectively, for the years 1989, 1999, 2002 and 2005, 8.97%, 12.13%, 15.31% and 15.69% of the total debits to the groundwater.

Table 1 also shows that starting from the years when the extracted rated by pumping have increased, flows out of the water via the coast have vanished (inversely to the flow direction).

The aim of this work is to highlight the current state of water vulnerability in Bouteldja aquifer. This will be performed using the well-known GALDIT method. The innovative thing in this paper will be the joint use of geostatistical approach to better characterize the spatial variability of the studied variables and easily compare it to background maps (geology, petrology, etc.).

GALDIT approach has been first developed during the project "EU–India INCO-DEV COASTIN" (Michaud et al. 2003) whose objective was to determine the vulnerability of coastal aquifers to the intrusion (Chachadi and Lobo-Ferreira 2005). This approach is based on the hydrogeological characteristics (depth of the water body, thickness of the aquifer), morphological (distance from the coast), hydrodynamic (transmissivity) and chemistry (impact of marine intrusions). The parameters of this method are based on the physical characteristics that can affect the marine intrusion (Agarwadkar 2005).

Many coastal aquifers were studied using GALDIT model. Namely, the groundwater of Guerbes–Annaba in Algeria (Guezgouz et al. 2013), the groundwater of Mahdia, in Tunisia (Saidi 2011), the groundwater of Mnasra-Gharb, in Morocco (Batchi et al. 2014), in South Florida USA (Tasnim and Tahsin 2016), (Kardan Moghaddam et al. 2017) and the Quaternary layer of Collo, in Algeria (Boulabeiz et al. 2018).

As it will be shown, in the sections below, we can already remark that the principal weaknesses of the GALDIT method reside in its discrete aspect as well as the smoothing effect of the calculated GALDIT parameter. In other terms, there is melting pot effect of the important continuous aspect of some variables within the obtained parameter.

To deal with these weaknesses and the few number of data, the GALDIT approach will be also optimized by the joint use of geostatistics and of geographical information system (QGIS), in order to model and estimate the phenomenon in each mesh of the study area taking into account its structure and its correlation in space, thereby making best estimates. The study relies on the theory of random functions and addresses the analysis of the phenomenon in probabilistic terms (Djoudar 2014).

Software Isatis (version 7.0) (Geovariances 2007) is a tool for geostatistics allowing implementation of geostatistical estimation techniques. It requires a thorough prior analysis of the experimental data, to determine the characteristics of these data and to describe and model the spatial structure of the studied variable. It allows to obtain, by kriging, a robust mapping to quantify uncertainties and risks. Then, these cards allow the user to identify and treat the anisotropies and data anomalies using appropriate statistical representations (base map, histogram, variogram, cloud variographic).

QGIS (version 2.18.24) https://www.qgis.org/fr/site/about/index.html is a Geographical Information system (GIS) user-friendly distributed under GNU General Public License. It is an official project of the Open Source Geospatial (OSGeo) Foundation. It is compatible with Linux, Unix, Mac OS X, Windows and Android and many formats, vector, raster, database, and built-in features.

Study area

The study zone is situated in the eastern part of Algeria, at the extreme east of the alluvial plain of Annaba, between the longitudes 08°36′00E to 09°12′00E and the latitudes 40°40′00N to 40°03′00N. It is part of the El Tarf Wilaya including the towns of Bouteldja and Berrihane. With an area of 116 km^2, the Bouteldja sand ridge belongs to the great side basin of the Mafragh (803 km^2) (Fig. 2).

The considered aquifer is bordered by the Mediterranean Sea, in the North, the Bouteldja plain in the South, the Mafragh basin, in the West and the Numidian Mountains of Bouteldja in the East. With a direction NW–SE, the Bouteldja mountains are culminating at the Djebel Koursi with an altitude of 346 m and the Rosa Cape to the extreme North East.

The study zone is characterized by a Mediterranean climate, mild and humid in winter and hot and dry in summer. For the period 1978–2005, December is the wettest month with an average rainfall of 107.4 mm, while July is the driest with about 4 mm at the Salines station.

For the same period, the highest monthly mean temperatures are noted essentially during the summer period (June–September) with temperatures between 20 and 25.5 °C, while the lowest temperatures, from 10 to 12.5 °C, are observed in winter (December–March) with a minimum temperature in January of about 10.5 °C. The other months show intermediary temperatures (14–20 °C) (Aichouri 2016).

The water balance (1971/1972–2002/2003), made by (Affoun 2006), gives a yearly mean water deficit of about 423.04 mm at the Cheffia Dam, 419.09 mm at the Salines in Annaba and 400.78 mm at Bouhadjar, with a surplus of 310.50 mm, 182.87 mm and 133.80 mm, respectively.

According to the same source (Affoun 2006), groundwater, less important in comparison to the superficial resource, is already exploited in an optimized manner (94.1 hm^3 on 97.5 hm^3) that is 96.51% of the renewable water reserves of the Mafragh. This volume is extracted from the aquifer of the sand ridge of Bouteldja as well as from the aquifer of the deep gravel aquifers of the Annaba plain.

From a geological point of view, the studies realized in the area, under Joleaud (1936), Hilly (1962), Vila (1980), Lahondère (1987), Gleizes et al. (1988), Hammor (1992) and Sebaïti (2010), show the existence of two types of formations: metamorphic and sedimentary (Fig. 3).

The stratigraphical scale of the terrains on the surface is difficult to reconstitute due to the extreme tectonic complexity of the area. Nevertheless, we can recognize the terrains from primary to recent quaternary periods (Toubal 1998).

The quaternary period, with a thickness of 32 m, is constituted by an alternation of grey-yellowish sands very fine to coarse and fine plastic to yellowish clays very sandy. It constitutes the reservoir rock of the aquifer system of Annaba–Bouteldja (Figs. 3, 4).

The hydrographic network is entirely absent on the sands of the sandbank of the dune giving rise to 'Garâats' or to 'Nechâas' (Garâats el Khoubzi et Nechâas Oum El Agareb et Righia) (Affoun 2006). It is bordered from the west by the Bou Namoussa and Kebir rivers, which start in Tunisia. These two rivers converge at 1.7 km from the sea to give rise to the Mafragh River.

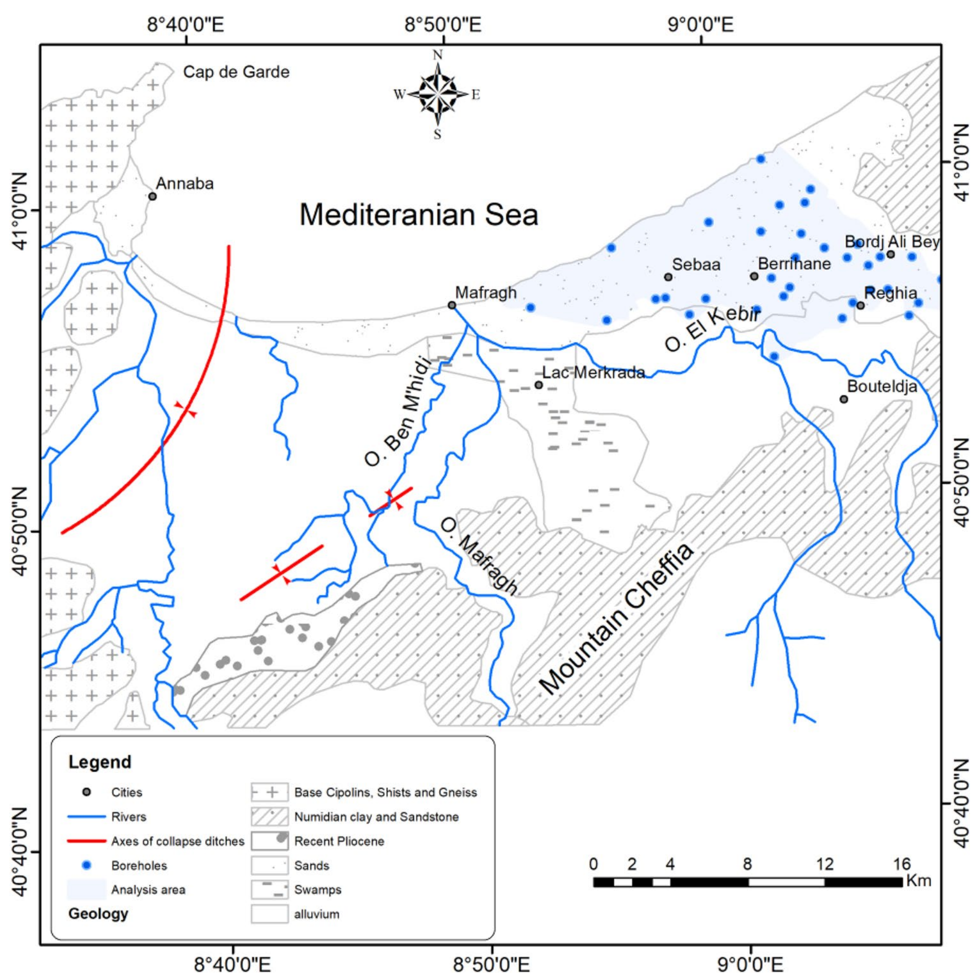

Fig. 3 Simplified geological map of the Annaba plain (Toubal 1998)

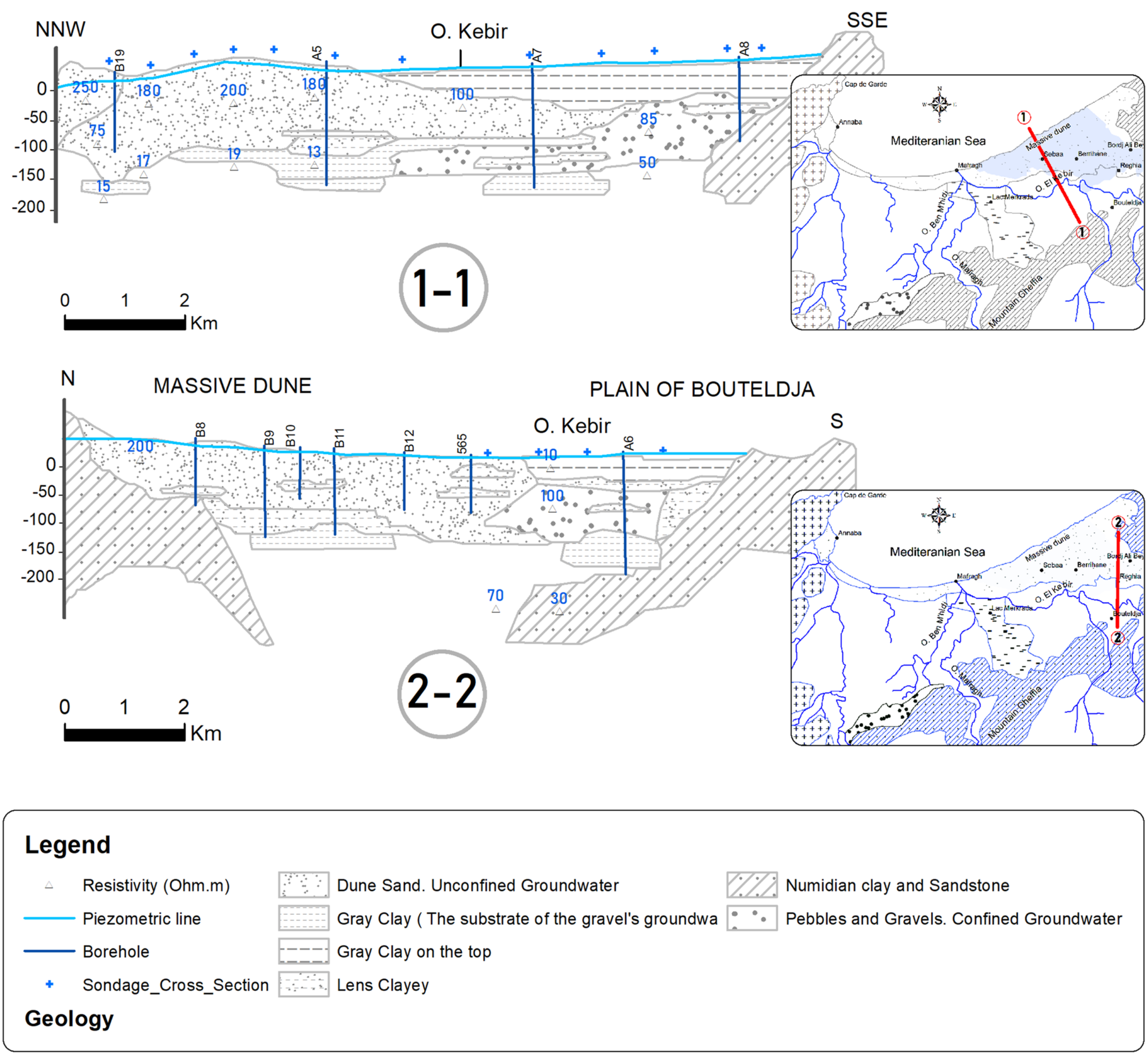

Fig. 4 Cuts through the plain and Bouteldja dune massif Cut (1-1) NNW–SSE and Cut (2-2) N–S (Aichouri 2016)

The eastern part of the large sand ridge area is drained by three tiny rivers which flow into the Oued Kebir at Bouteldja.

From the hydrogeological point of view, the aquifer of the Bouteldja dune hill constitutes the eastern borderline of the aquifer system of Annaba. It is a free aquifer contained in thick wind sands from 20 m to the east to 120 m to the west (Fig. 5).

The piezometers studied by different authors (Toubal 1998; Hani et al. 2003; Assassi et al. 2004) show that the supply for the aquifer is mainly through rain water infiltration, and also by diffuse streaming on the Djebel Koursi reliefs groundwater flow to the north, towards the sea and the terraces of Oued Kebir to the east and to the south, following a water divide line.

The lack of recent piezometer data (water depth) in the 36 water points of the study area made it impossible to use any map, but an old one, established by Kherici in 1985 (Fig. 6). As a result, the direction of flow inversion is not visible in the northeast part of the study area, as shown by recent research (Sebaïti 2010; Haïed 2015; Aichouri 2016).

The eastern part of the dune is characterized by a progressive increase of the thicknesses, under a primary east–west direction from the Bourdim River (20 m) to the Bouglès River (75 m), then a secondary NE–SW direction from Djebel Koursi (70 m) towards Necha Righia (150 m).

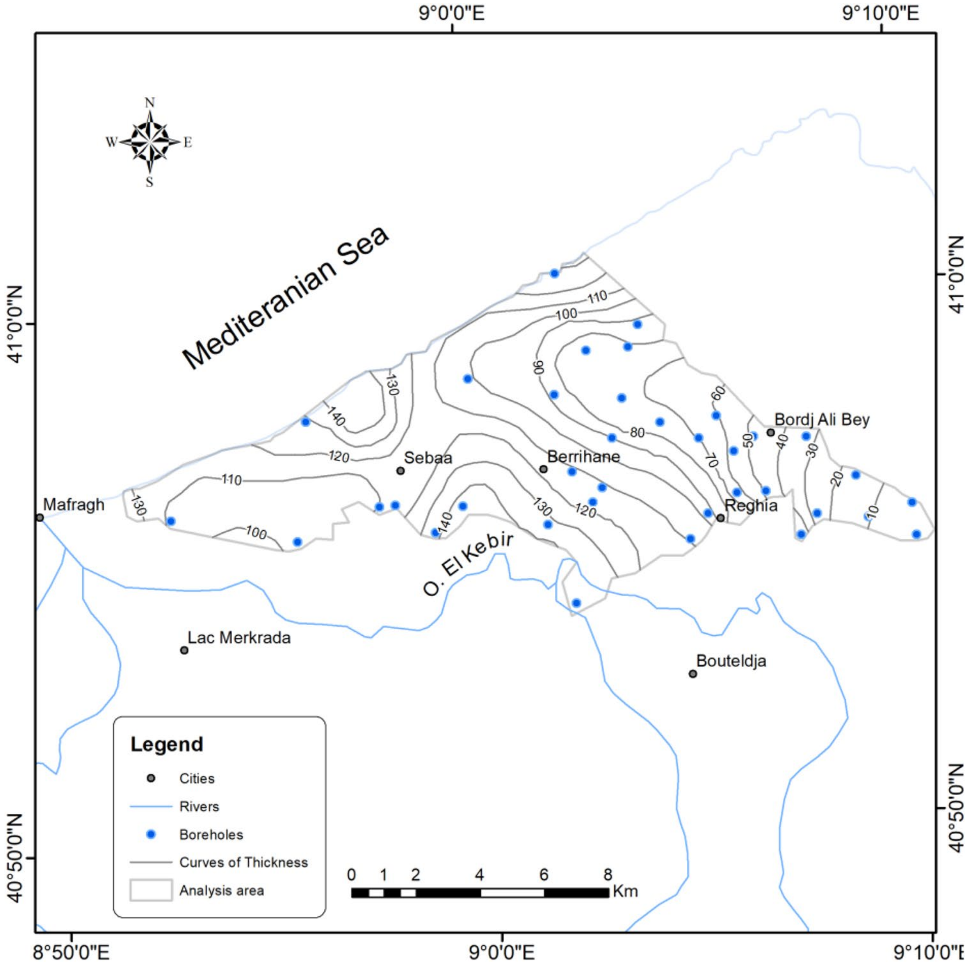

Fig. 5 Isopach map (equal thickness) of dune sands (Aichouri 2016)

The central zone presents a relatively constant thickness, estimated to about 150 m. In the entire eastern part of the dune, the map shows very important thicknesses of alluvial deposits, particularly straight up of the streams (waterways) recognized by the geophysical prospection (Toubal 1998; Kherici 1985; Ramdani 1996; Aichouri 2016) (Fig. 5).

It constitutes a real water reservoir of natural water towering over the plain of El Kebir River; it is an aquifer reservoir with a high conducting function. It is fed by the efficient infiltration, presents a low or weak inertia and responds promptly to the different external impulses (Toubal 1998).

The water is supplied by the infiltration of precipitation (25–40%) and the water that runoff Numidian mountains which have a flow of about 1100 l/s or 35×10^6 m^3/year (Energoprojekt-Enhyd 1992).

Furthermore, Toubal's research (Toubal 1998) showed that the of storage coefficient values were contained between 4 and 21% with an underground storage increase from Djebel Koursi towards the interior of the plain with values particularly high in the Hannaya and Righia areas.

As for the transmissivities, they vary from 3×10^{-5} to 1×10^{-2} m^2/s. The values of the storage coefficient are in average of 11.5% for the dune sands and correspond to a free aquifer (Sadoune 2012).

Materials and methods

GALDIT method

GALDIT is an indexation vulnerability methodology which uses intervals, classes and weights. It was developed as preliminary tool to predict underground water subject to marine salt water intrusion (Zaarour 2017).

The GALDIT method has been developed by Chachadi and Lobo-Ferreira (2001), within the framework of the Euro-Indian COASTIN (INCO DEV program of the 4th PRCD) (Dörfliger 2011).

The first application results of this model have been obtained in the coastal regions of Goa in India and Algarve in Portugal by Chachadi and Lobo-Ferreira (2005) and Lobo-Ferreira et al. (2005). An indexation of the vulnerability and a classification of the potentialities of a salted

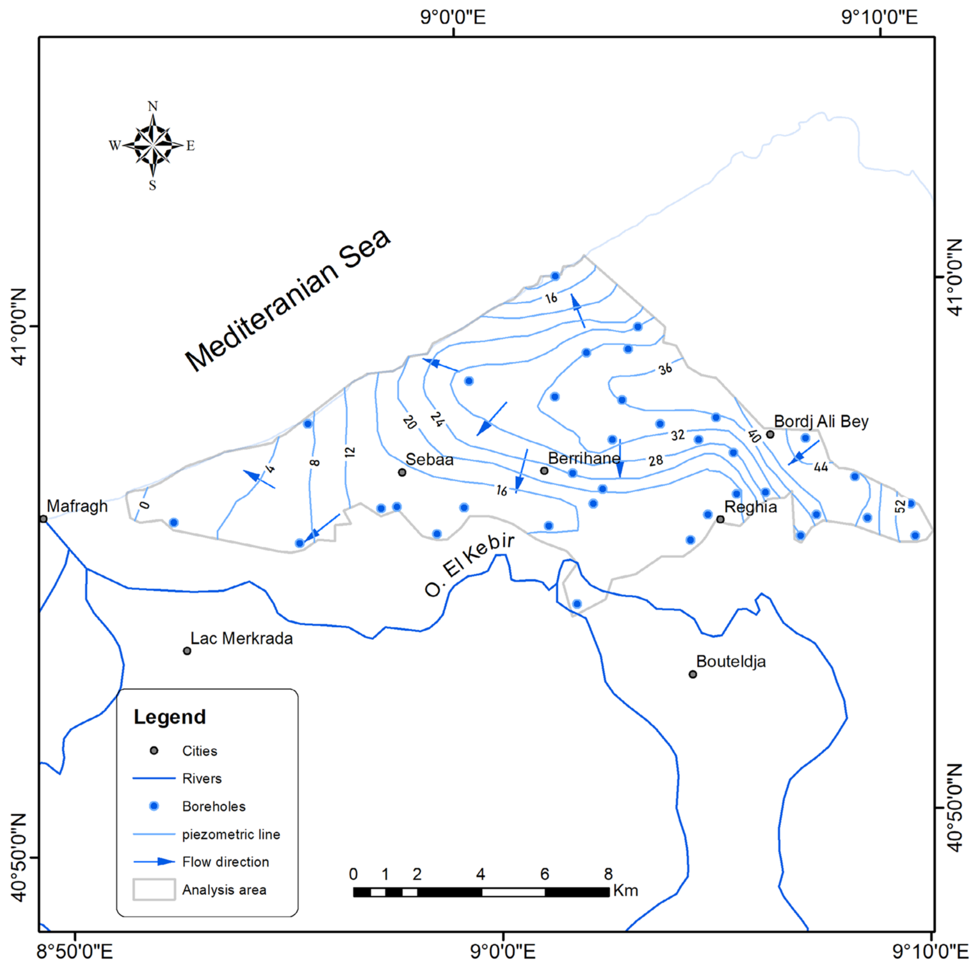

Fig. 6 Map of piezometric map of the dune massif of Bouteldja 1982 (Kherici 1985)

intrusion in a given geological context were established from the six GALDIT parameters (Dörfliger 2011).

The calculation of the GALDIT index is based on six parameters, which are: (*G*) groundwater occurrence (aquifer type; unconfined, confined and leaky, confined); (*A*) aquifer hydraulic conductivity; (*L*) groundwater level above sea level; (*D*) distance from the shore (distance inland perpendicular from shoreline); (*I*) impact of existing status of seawater intrusion in the area; and (*T*) thickness of the aquifer being mapped.

This index is a weighted ration where each parameter receives a weight corresponding to its relative role. It is defined by the following formula:

$$\text{Index-GALDIT} = \frac{\sum_{i=1}^{6} P_i R_i}{\sum_{i=1}^{6} P_i}, \tag{1}$$

where P_i weights attributed to each parameter (i) according to its level of influence on the salted intrusion. The importance goes from 1 (weak influence) to 4 (strong influence). R_i the rank or the value which varies from 1 (weak vulnerability) to 10 (high vulnerability) (Najib 2014).

In order to get a better appreciation of the vulnerability values, the geostatistical approach has been performed for the continuous variables *A, L, T* and *I* (see Table 1; Fig. 4). For that, the study area of Bouteldja (area 116 km^2), has been discretized into 60 m × 60 m squared parts which gives a number of 150,325 points to be estimated by kriging.

For computations, this work has used existing multidisciplinary data concerning the study area (geological, structural, geophysical, hydro-geological and hydro-chemical). Data analysis has been mainly performed using *ISATIS7* software (statistical study, semi-variograms analysis and data cross-validation). The *ISATIS7* software has also allowed Kriging maps calculations.

Geostatistical computations

The principal tool in geostatistical computation, modeling and kriging is the semi-variogram. A semi-variogram simply consists in calculating the spatial variance $\gamma_{\text{th}}(u, u+h)$ (or theoretical semi-variogram) between the observations in u and u plus a distance h farther $(u+h)$ [Eq. (2)]. This theoretical equation has been simplified to make the experimental calculations

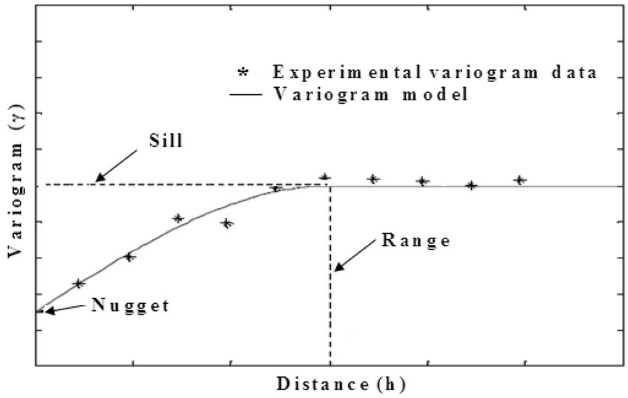

Fig. 7 Example of experimental semi-variogram (points) and a fitted theoretical model (curve). a is the range of the studied phenomenon and $C0$ and C are, respectively, the variances to $h = 0$ and $h = \infty$ (Benamghar 2002)

easier [Eq. (3)]. Notice that $\gamma(h)$ depends only on the distance h between observed samples (Baillargeon 2005; Chilès 2004):

$$\gamma_{\mathrm{th}}(u, u+h) = \gamma(h) = \frac{1}{2}\mathrm{Var}[Z(u) - Z(u+h)], \tag{2}$$

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(u_i) - Z(u_i + h)]^2, \tag{3}$$

where $Z(u)$ is the stationary random variable representing the variable studied at the point u. u is the position where the variable $Z(u)$ was sampled. h is the distance between two points on the ground. Is varied from zero, following the steps set by the operator, to capture all pairs of incoming samples in this lag of distance to calculate the variance $\gamma(h)$. $N(h)$ is the number of sample pairs separated by distance h.

There are two types of semi-variograms: omnidirectional and directional. The first compares samples two by two, using $\gamma(h)$ (Eq. 3) whatever is the direction in space. The second is more restrictive since it is conditioned by the operator to a particular direction in space. These two tools are complementary (Fig. 7).

In practice, the omnidirectional semi-variogram allows to see if there are more continuous directions than others for a considered variable in the studied space. This is possible by mapping the omnidirectional semi-variograms in the plan (rose diagram) then by analyzing their ranges (range a, Fig. 8). If ranges are invariant with direction then the phenomenon is declared isotropic (Fig. 9), otherwise it is

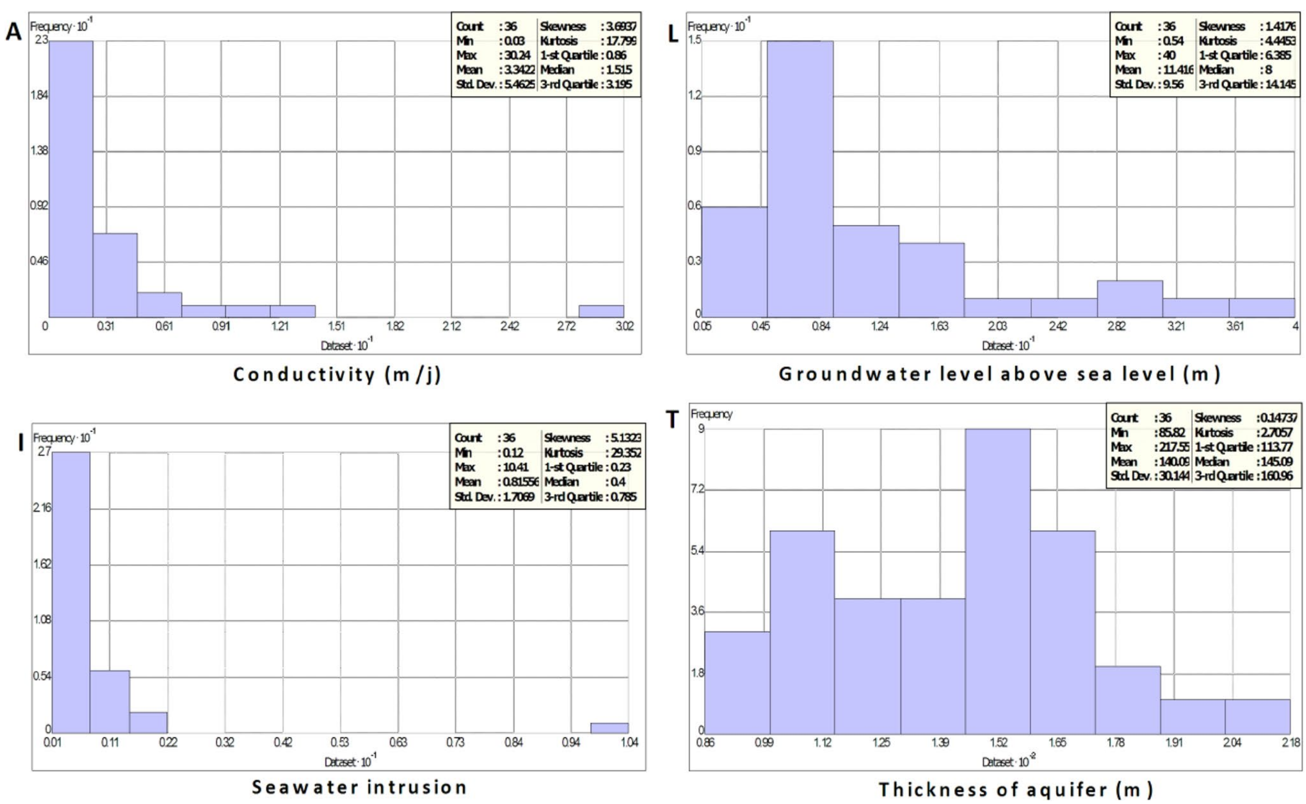

Fig. 8 Histograms of the variables (*A*, *L*, *I* and *T*)

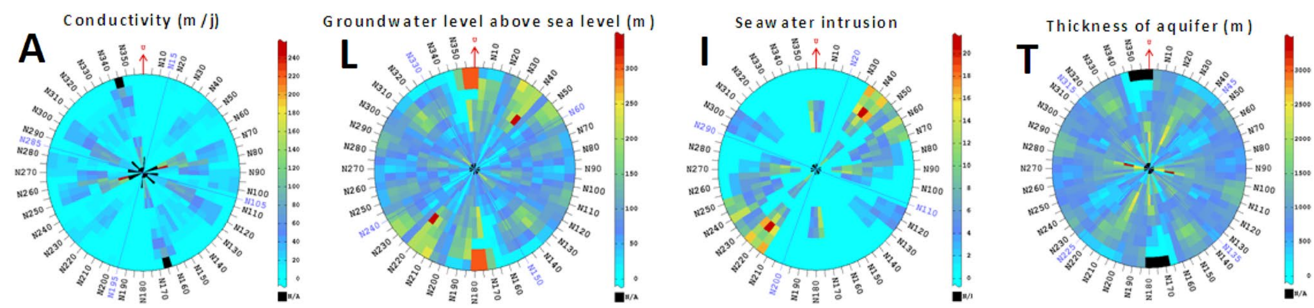

Fig. 9 Rose diagrams of calculated semi-variograms of *A, L, I* and *T* variables (using Isatis7)

anisotropic. The latter case is rare and complex; it requires determining the main directions of maximum and minimum continuity and should be taken into account in kriging operation.

The geostatistical analysis was performed following several steps before final kriging maps. The first step was the experimental semi-variograms calculation and modeling of each variable in the sampled area.

The omnidirectional experimental semi-variograms (EVS) for variables (hydraulic conductivity) *A*, (groundwater level above sea level) *L*, (thickness of the aquifer) *T* and (impact of existing status of seawater intrusion) *I*, have been calculated in the isotropic case because of the erratic behavior of the directional structures. The EVS range distances have varied from 550 to 750 m. The details of these semi-variogram calculations are summarized in Table 1 and in Fig. 4.

In this work, the best experimental omnidirectional semi-variograms (direct ESV) were obtained through values levels of *h* (lag distance) of 550 m, 750 m, 650 m and 730 m, respectively, for the variables *A, L, T* and *I* (Table 2). The rose diagrams of these semi-variograms present almost erratic structures (Fig. 8) suggesting the absence of any spatial trend (absence of isotropy). For this reason, the kriging operation which will be performed with these variables in sections below, can use $\gamma(h)$ omnidirectional models regardless of the direction in space.

Table 2 summarizes results of experimental semi-variograms calculations as well as the adjusted models for each variables (*A, L, T* and *I*). All of these variables showed a more or less structured spatial correlation with a generally spherical model of low nugget effect ($C0$ tends to zero).

There is an exception with the marine intrusion *I* variable which is modeled as Gaussian with a null nugget effect $C0=0$ (Fig. 10). It is to be recalled that the Gaussian model is an indication of a perfect spatial continuity especially when $C0=0$.

Hence, we can already deduce that marine intrusion *I* into the Bouteldja aquifer is really present and continuous, because it shows a perfect continuity in space. It is not the result of an error of measurement, or specific to a limited zone, but well present in all the studied areas.

Table 2 Experimental semi-variograms and fitted models of studied variables, along with corresponding parameters (range, sill, nugget effect)

Variables	Experimental semi-variogram omnidirectional (ESV)		Number and type of structure		Range (m)	Sill
	Lag distance (m)	Number of lag distance				
Conductivity (m/J)	550	6	1	Nugget effect model	–	1.74
			2	Spherical model	1621	27.39
Height of groundwater level above sea level (m)	750	10	1	Nugget effect model	–	13.02
			2	Spherical model	2247	69.55
Thickness of aquifer (m)	650	10	1	Nugget effect model	–	101.2
			2	Spherical model	1947	805.2
Seawater intrusion	730	6	1	Gaussian model	2198	2.27

Modeling parameters

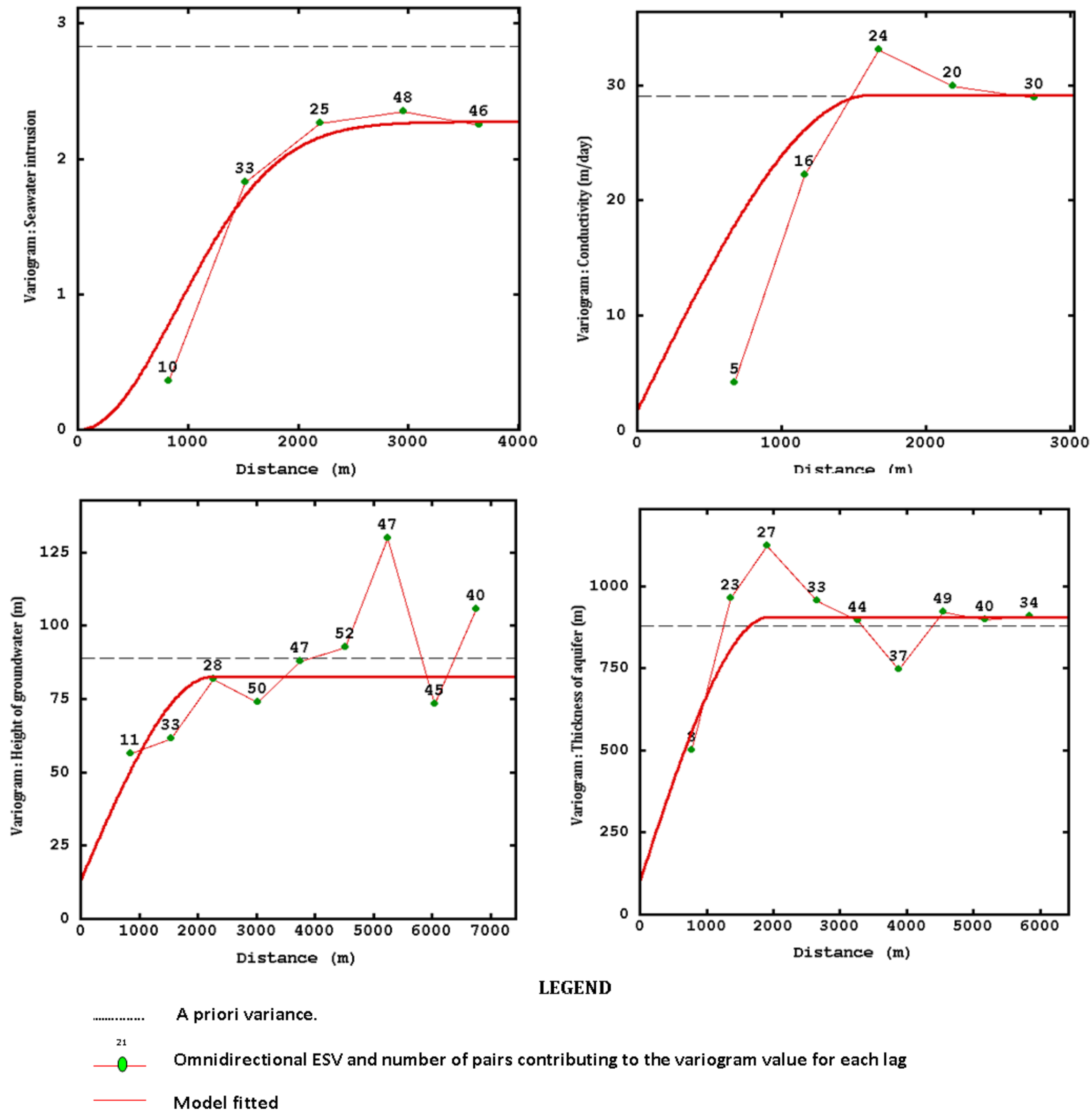

Fig. 10 Model semi-variograms (curves) fitted to the experimental semi-variograms (points) (the numbers on the points correspond to the number of pairs of samples used in the calculation of $\gamma(h)$ at this distance)

Results and discussion

Map of the type of aquifer (*G*)

The groundwater is stored in geological formations (porous or cracked formations), the latter could either be confined (captive), semi-confined (semi-captive) or non-confined (free). Therefore, the free aquifer, often subject to intensive pumping, is much more exposed to the marine intrusion than the semi-confined one. The semi-captivity maintains the hydraulic pressure to a minimum, because of the associated leakages to adjacent aquifers, thus protects the aquifer from marine pollution.

In the opposite, a captive aquifer is more vulnerable because of the existence of important depression cones and the immediate expulse of water from wells during the pumping. In this case, the range value is the highest (10) (Dörfliger 2011).

In this case study, the aquifer is entirely free. The GALDIT parameter (*G*), represented in Fig. 11g, is estimated to a value of 7.5, given in Table 3.

Note that the variables *G* (type of aquifer) and *D* (distance from the shore) are discrete variables, so we do not need kriging.

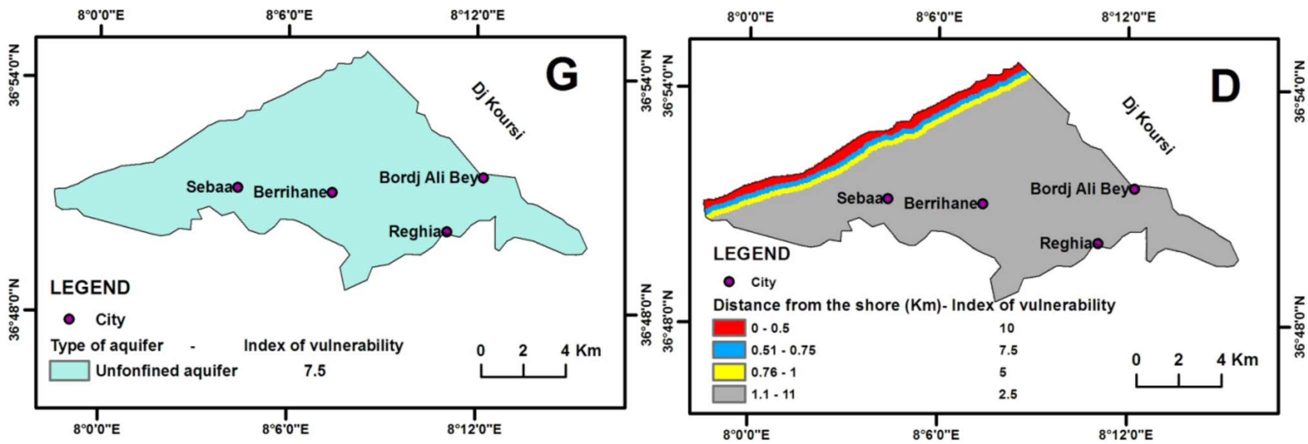

Fig. 11 Parametric maps: (*G*) type of aquifer, (*D*) distance from the Mediterranean Sea

Table 3 Synthesis of the weights and ranges by the GALDIT method (Dörfliger 2011)

Parameters	Weight	Range			
		Very weak	Weak	Average	High
		2.5	5	7.5	10
G: type of aquifer	1	Restrained	Semi-captive	Free	Captive
A: hydraulic conductivity (m/day)	3	< 5	5–10	10–40	> 40
L: depth of the aquifer/sea level (m)	4	> 2.5	1.5–2	1–1.5	< 1
D: distance to the shore (m)	4	> 1000	750–1000	500–750	< 500
I: impact of the marine intrusion (ppm)	1	< 1	1–1.5	1.5–2	> 2
T: thickness of the aquifer (m)	2	< 5	5–7.5	7.5–10	> 10

Map of distance from the shore (*D*)

This parameter has not been kriged, but has been estimated by calculating the distance perpendicular to the shore (bird flies) from the center of each mesh of the field of study that were discretized in square 60 m × 60 m. In attributing the row corresponding to each distance according to Table 3 and was used to calculate the distances following three distances 500 m, 750 m and 1000 m.

The more a water point is near the shore, the more the impact would be bigger and then the vulnerability would be with a maximum range of 10. This value decreases as soon as we get away from the shore.

The map of *D* variable of the Bouteldja aquifer (Fig. 11d) shows four vulnerability bands. To the north, a band with a very strong to strong vulnerability with a rank of 10–7.5, stretched parallel to the shore on the axis Mafragh–Cape Rosa. Then comes a band of medium vulnerability with a rank 5 in the direction WSW–ENE on a distance not exciding 1 km for the three distances.

Finally, the band of weak vulnerability, with a rank of 2.5, occupies the remaining area of the aquifer.

Table 4 gives a brief description of the results of statistical calculations applied to the four variables (*A, L, I* and *T*) of the GALDIT method.

Map of aquifer conductivity (*A*)

The hydraulic conductivity map (*A*) was established by kriging in Isatis7 of the conductivity data of the Bouteldja dune aquifer (Annex 1). The conductivity values vary from 0.22 to 28.10 m/day. The hydraulic conductivity of the aquifer is weak for the major part of the aquifer (< 5 m/day), which corresponds to a rank equal to 2.5 for almost the entire aquifer according to Table 3.

Very few small areas with a range equal to 5 are found around Bordj Ali Bey and the extreme south-east of the study area where the conductivity varies from 5 to 10 m/day. This can be explained by the dominating lithographic nature existing in these areas. There is alternation of very fine to coarse grey-yellowish sands and of fine to coarse yellowish plastic clays very sandy.

The remaining area at the extreme south-east is confined to the precedent layer and is characterized by a mean

Table 4 Descriptive statistics of the variables

Variables	No. samples	Aquifer hydraulic conductivity (m/J)	Groundwater level above sea level (m)	Thickness of aquifer (m)	Seawater intrusion
Minimum	36	0.03	0.54	85.82	0.12
Maximum		30.24	40	217.55	10.41
Mean		3.34	11.42	140.05	0.816
Standard deviation		5.46	9.56	30.144	1.71
Variation coefficient		1.612	0.826	0.212	0.478
Skewness coefficient		3.69	1.417	0.147	5.132

vulnerability with a range of 7.5 for a conductivity > 10 m/day at the foothills of Djebel Koursi (Fig. 12a).

Map of aquifer level (*L*)

This factor determines the hydraulic potential able to push back the marine front towards the sea. In general the values concerning the minimum spot lines of water below the sea level remains the most representative, since they attest to the strongest possible vulnerability to this salted edge.

The points reported by the ANRH since always, are grouped in a very small space, which does not allow making reliable extrapolations. So we took into consideration the values of the piezometer level (low water 2005).

The depths of the Bouteldja aquifer levels obtained through geostatistical Kriging vary from 5.5 to 24 m (Annex 1). Therefore, the obtained map includes an only very weak vulnerability class with a 2.5 range on the entire studied area (Fig. 12l).

Map of impact of existing intrusions (*I*)

The values of the $[Cl^-/(CO_3^- + CO_3^{2-})]$ ratio of the Bouteldja sand ridge aquifer are distributed over four intervals. The calculation of the latter is based upon the chemical analysis of the lowest water 2005 provided by ANRH Annaba (Agence Nationale des Ressources Hydrauliques de Annaba).

The study of Haied et al. (2015) has shown that the Bouteldja dune aquifer was intensively exploited which

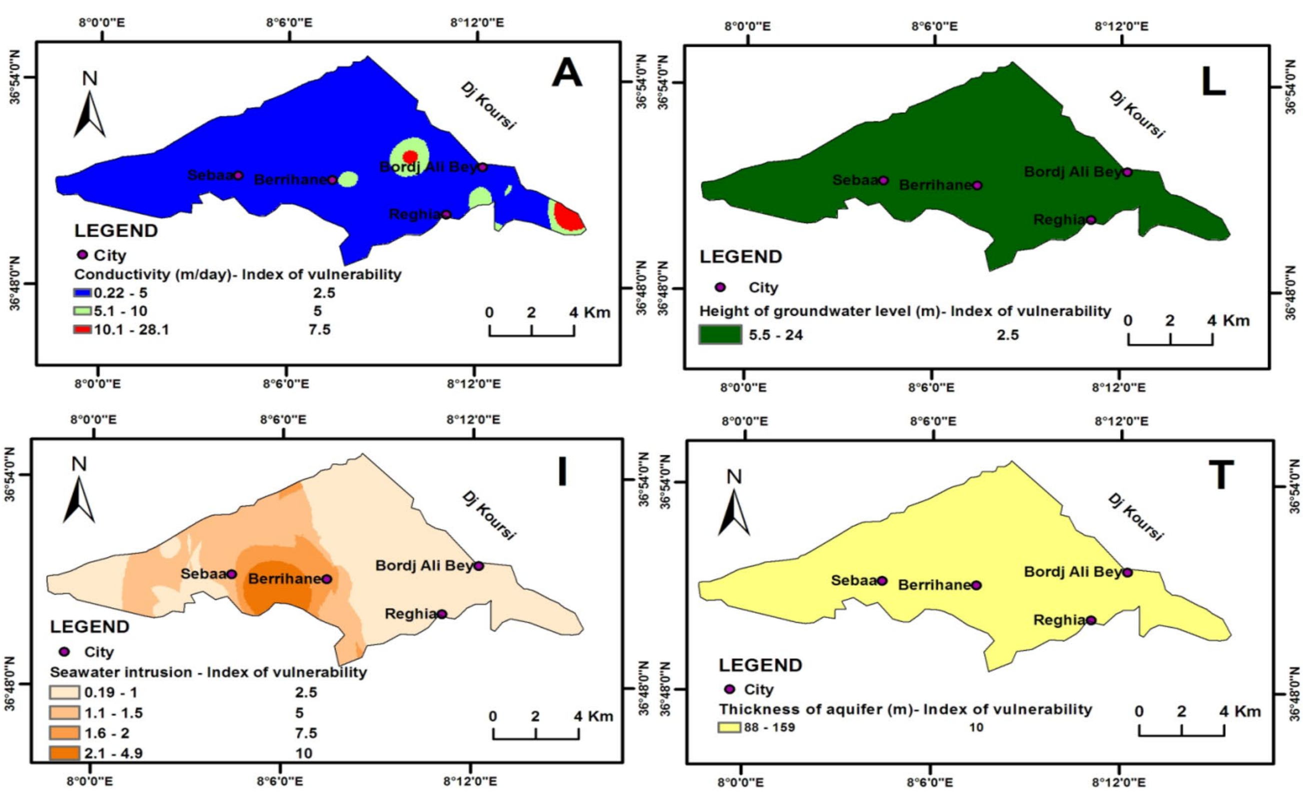

Fig. 12 Kriged maps of the four variables *A, L, I* and *T*

induced a decrease of the piezometric level and a marine intrusion. This is shown in Fig. 12i, which highlights the bands characterized by the high values of the ratio $Cl^-/(HCO_3^- + CO_3^{2-})$ of the aquifer (> 2) and medium (1.5–2) occupying entirely the central zone in the direction N/NW–S/SE (sea/continent). It corresponds to a high vulnerability (range = 10) and a medium vulnerability (range = 7.5), which are located to the south-west, due to the intensive pumping given the large thickness of the dune sands (about 120 m) (Fig. 6) as well as piezometric depression (Fig. 9).

For our part, we were able to confirm this marine intrusion of large magnitude by kriging *I* variable (Fig. 12i). In this figure we can see a south–north halo in the south-western part of the aquifer (Fig. 13). This anomaly corresponds perfectly to the same vulnerable area established by Attoui et al. (2012) (Fig. 14, red color). This intrusion could be explained by the high density of pumping wells in this area which has created a piezometric depression that made a call of sea water.

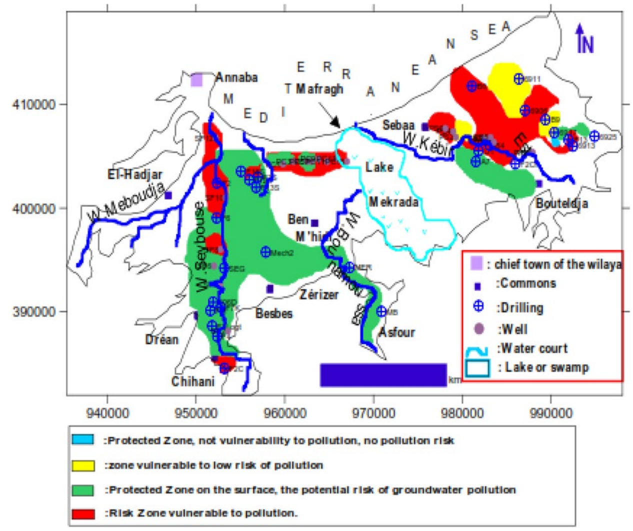

Fig. 14 Map of vulnerability and pollution risk of the different aquifers in Annaba Bouteldja region (Attoui et al. 2012)

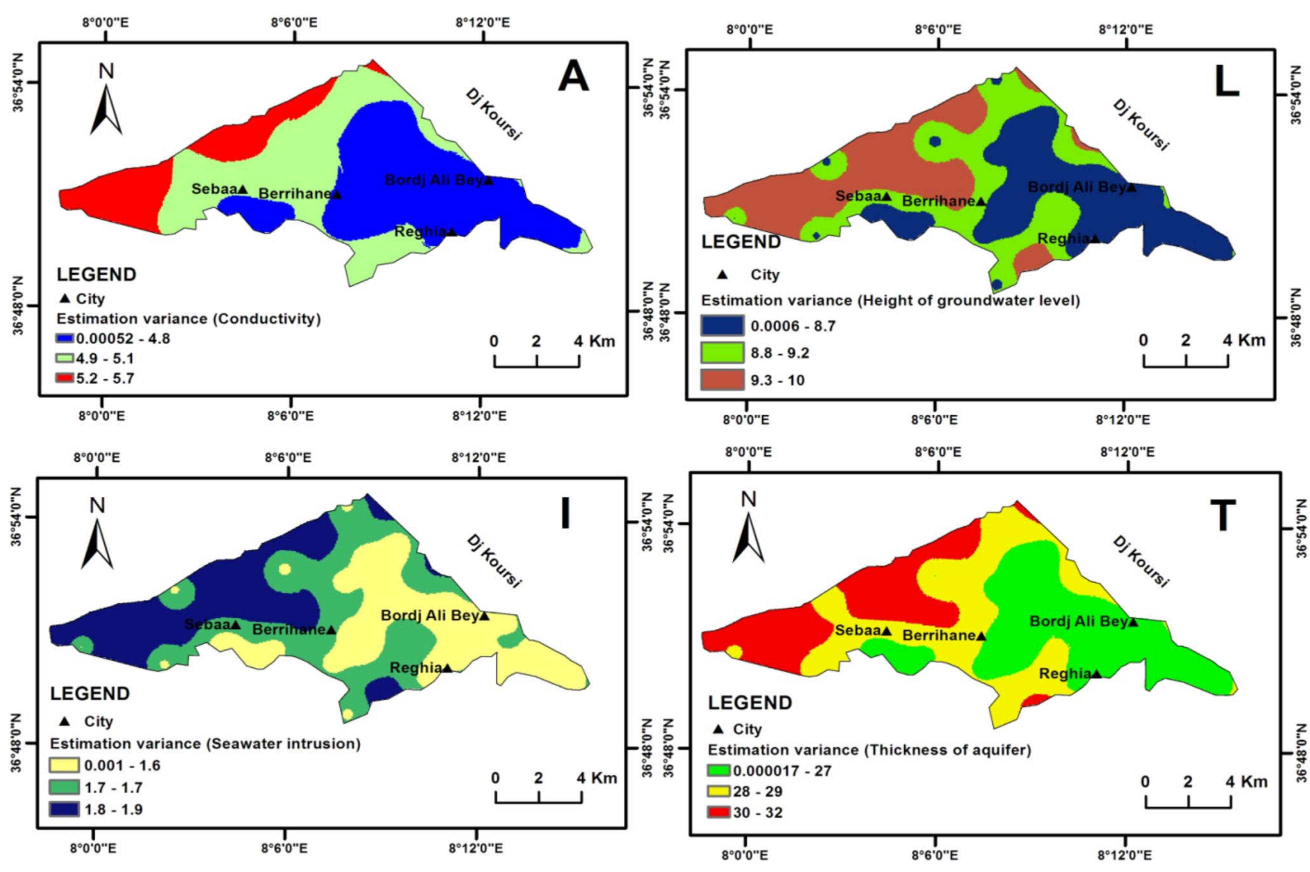

Fig. 13 Maps of estimation variances of variables (*A, L, I, T*)

Map of aquifer thickness (*T*)

The values of the saturated thickness of the free Bouteldja aquifer plotted from drilling logs (Annex 1) are all higher than 10 m, and more than 78% of the work shows a saturated thickness between 100 and 160 m. The mean value is around 119 m. This thickness being important and hence is a factor that increases the vulnerability of the aquifer, and thus the highest range with a value of 10 is then attributed to the entire aquifer (Fig. 12t).

Kriging of the GALDIT continuous variables

As discussed in the sections above, the continuous variables *A, L, I* and *T* spatial continuity modeling has led us to perform a kriging estimation of each variable all over the studied area. In this respect, four variables kriged maps *A, L, I, T* have been established (Fig. 12).

To appreciate the quality and accuracy of these results (Fig. 12), the same kriging computations are provided with their estimation variances, which are presented in Fig. 13. The estimation variance in geostatistics is a way to assess the quality and the reliability of the estimation (kriging) produced. When its value is high then this shows less reliable areas because of a lack of samples, for example. Meanwhile, low values of estimation variance shows an abundance of data samples and so an estimate more reliable. So we can point out, for the four variables of Fig. 12, that the areas with high density of surveys (center to south-south-west), estimation variance is the lowest while along the shore, where there are not many surveys, the kriging variance is higher.

Map of the GALDIT index of vulnerability

To produce the global GALDIT index vulnerability map, we have proceeded by estimating individually each variable (*G, A, L, D, I* and *T*) for all the 150,325 defined 60 m × 60 m meshes of the area.

Indeed, the four parameters *A, L, I, T* were kriged using the geostatistical computations discussed above.

Meanwhile, *G* and *D* parameters were assigned their weights according to Table 3 (proposed by Chachadi and Lobo-Ferreira 2005, Appendix 1).

Finally, values of global GALDIT index of vulnerability of the Bouteldja aquifer, computed using Eq. 1, are shown in Fig. 15 and resumed in Table 5.

On one hand, the GALDIT index map, Fig. 15, shows an average vulnerability (index values 5–6.17) occupying a 700-m littoral band extending in a WSW–ENE direction. On the other hand, it shows a low vulnerability range occupying the rest of the study area.

At first sight, we note that the results obtained by the GALDIT index map, greatly minimize the vulnerability of the groundwater table to salt water pollution. Indeed, these results do not confirm the dominant marine intrusion anomaly highlighted with the *I* variable map above (Fig. 12i).

Table 5 GALDIT index vulnerability classes (Dörfliger 2011)

Vulnerability class	GALDIT index
High vulnerability	> 7.5
Medium vulnerability	5–7.5
Low vulnerability	< 5

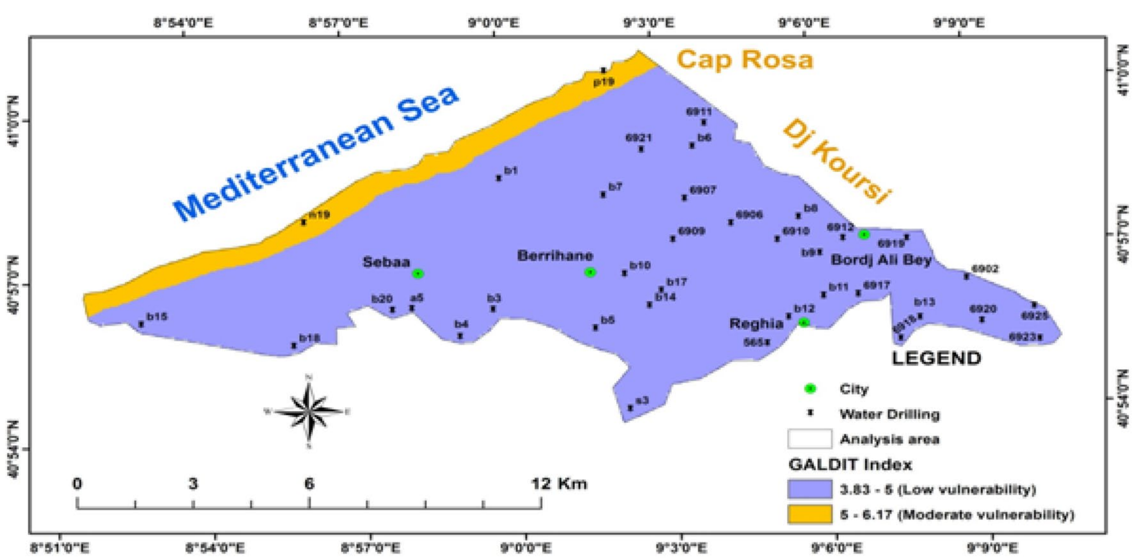

Fig. 15 Map of the GALDIT index vulnerability of the Bouteldja aquifer

Moreover, these results make a large difference with those obtained by Attoui et al. (2012).

Attoui et al. (2012) have classified the studied aquifer at high risk of pollution by combining the study of the alluvial plain pollution risk, based on the model of Kherici et al. (2010), and the high permeability of its geological formations, as well as the increased solicitation of the aquifer by various industrial uses, drinking water supply and irrigation.

Conclusion

The Bouteldja littoral aquifer is an important reservoir of groundwater in the extreme east of Algeria. This aquifer is under threat of intensive exploitation, associated with deficit of precipitation due to the global warming shaking our planet these last decades. This situation has exacerbated and aggravated the progression of the saltwater into the continent, as proved by various and recent research studies.

This study has proposed a new approach using the GALDIT method coupled with a geostatistical approach to capture the spatial variability of those continuous variables composing the GALDIT. The four continuous variables *A, L, I* and *T* were geostatistically modeled and kriged all over the study area (divided into 150,325 meshes of 60 m × 60 m). These results combined with the discrete variables data (*G* and *D*) were then used to evaluate the final GALDIT index for each one of these meshes.

The GALDIT index vulnerability map revealed mainly two levels of vulnerability:

- Average level, along the coast which could be probably strong to very strong; considering the sandy nature of the aquifer reservoir;
- Low level, in the rest of the study area. This could be explained by the protective role played by the clay lenses corresponding to ancient marshlands interposed in the sand formation of Bouteldja.

In addition, we have noticed that the marine intrusion *I* anomaly highlighted in the kriged map of Fig. 12i, curiously does not appear in the GALDIT final map Fig. 15.

This is probably due to a strong dilution effect of GALDIT index, which is in fact a weighted average flattening the results to the point of masking an important anomaly of marine intrusion. Note that the latter would not be shown without a geostatistical investigation.

For this reason it would be preferable to use the GALDIT index final map just as a summary estimate of the groundwater vulnerability. To complete this result, one has to consider the other variables maps established by kriging to better appreciate each phenomenon's part.

For a better approach to the state of vulnerability of the groundwater table, it will be also necessary to combine it with other methods involving other important variables such as the nature of the saturated zone, unsaturated zone, the type and slope of the ground and the recharge of water table.

Finally, it has been shown, in our case study, that the GALDIT approach for vulnerability of groundwater pollution cannot be, alone, a good decision-making tool. It should be preferably coupled with other strong methods such as geostatistical modeling.

Acknowledgements We would like to thank Professor Abdelkrim Khaldi of the Laboratory of Rheology, Transport and Treatment of Complex Fluids (Department of Hydraulics, USTO-MB, Oran) for his valuable advice. Also thanks are due to the director of the National Agency of Hydraulic Resources (ANRH) of Annaba.

Annex 1

Hydrodynamic characteristics of the drilling inventoried in the sand ridge of Bouteldja (Haddad 2017).

Drillings	*X* (m)	*Y* (m)	Depths of the body of water/sea level (m)	Thickness (m)	Conductivity (m/j)	$C^{l-}/(HCO^{3-}+CO^{3-})$
p 19	983,800	414,100	10	120.02	1.56	1.2
b 01	981,100	410,800	40	161.4	0.03	0.43
b 03	980,950	406,820	6.52	145.4	1.81	10.41
b 04	980,100	406,000	6	108.05	0.84	0.12
b 05	983,600	406,250	10.75	126.33	0.72	0.43
b 06	986,100	411,800	7	217.55	0.41	0.19
b 07	983,800	410,300	0.54	139.4	1.56	0.16
b 08	988,850	409,650	1.5	157.92	0.76	1.06
b 09	989,400	408,550	13.56	170.48	1.42	1.7
b 10	984,350	407,900	6.55	145.02	6.26	1.38
b 11	989,500	407,250	8.62	145.15	0.86	0.29
b 12	988,600	406,600	16.57	85.82	3.11	0.29
b 13	992,000	406,600	6.98	172.05	0.51	0.21
b 14	985,000	406,950	7	132.18	0.68	0.97
b 15	971,850	406,350	13	189.1	1.30	0.4
b 17	985,300	407,400	8	151.19	1.64	0.25
b 18	975,800	405,700	1	111.36	1.12	0.3
b 19	976,050	409,450	3	151	0.95	0.4
b 20	978,350	406,800	7.43	160.52	1.04	0.16
6902	993,200	407,800	1.85	174.92	0.86	0.47
6906	987,100	409,450	7.87	119.87	13.96	0.16
6907	985,900	410,200	25	173.8	1.81	0.13
6909	985,600	408,950	6.25	140.19	3.28	0.25
6910	988,300	408,950	0.96	164.34	2.42	0.19
6911	986,400	412,500	8	116.18	2.68	0.31
6912	990,000	409,000	18	157.18	2.68	0.3
6917	990,400	407,300	4.96	98.5	8.64	0.5
6918	991,500	405,950	30	151.52	6.32	1.2
6919	991,650	409,000	13.71	136.43	3.36	1.21
6920	993,600	406,500	14.58	101.46	0.84	0.4
6921	984,780	411,690	9.46	149.25	3.46	0.52
6925	994,950	406,950	19.33	86.98	30.24	0.6
a 5	978,850	406,850	27	163.87	1.30	0.4
s 3	984,500	403,800	35	105	1.30	1.3
565	988,050	405,800	7	109.16	1.12	0.18
6923	995,100	405,950	8	104.61	9.42	0.29

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