GLL

Geomatics, Landmanagement and Landscape No. 1 • 2025, 119–145

ISSN 2300-1496 https://doi.org/10.15576/GLL/200413

Research paper

Received: 30.10.2024
Accepted: 21.01.2025
Published: 31.03.2025

Assessment of the vulnerability and sensitivity of groundwater for drinking water supply and irrigation: The case of the Mitidja alluvial aquifer (Northern Algeria)

Mohamed El Amine Khelfi[1, ✉] 0009-0004-1077-2802
Dahbia Djoudar Hallal[2] 0000-0002-6168-1060
Enrico Guastaldi[3] 0000-0002-5756-3539
Malika Alili[4] 0000-0002-2976-3875
Mohamed Nadri[4] 0000-0001-8739-0184

[1] University of Blida 1, RLPPWR, Algeria
[2] National High School of Hydraulics (NHSH), Algeria
[3] GEOexplorer Impresa Sociale S.r.l., Italy
[4] Higher Normal School (HNS), AEBL, Algeria
✉ Corresponding author: e.khelfi@ensh.dz

Summary

The aim of this study is to combine the hydrochemical data, geostatistical methods, and numerical approaches with the water pollution vulnerability index of the Mitidja alluvium. This index is obtained by applying the DRASTIC model and a numerical rating system to develop a methodology based on the water sensitivity index. The socio-economic development has led to the overexploitation of groundwater and surface water resources, coupled with insufficient rainfall, which has exacerbated the sensitivity and vulnerability of this precious resource. Compared to previous studies, the most recent sensitivity map serves as an important decision support tool for relevant authorities. According to the survey, this index was very low, accounting for 45.43% of the total drinking water area in 2010. It decreased to 8.25% and later increased to 28.06% in 2018. The high and very high sensitivity index to water pollution (SI) accounted for 5.34% and 9.87% in 2010, and 19.77% and 15.78% in 2018. The variation in irrigation water sensitivity was similar that of drinking water sources (DWS). The medium and high sensitivity indices (SI) increased from 27.21% and 18.20% to 37.19% and 42.01%, reflecting a significant and alarming increase in groundwater sensitivity, vulnerability, and pollution within the study area. The results of the geostatistical approach yielded some interesting results, considering the water intended for drinking water supply and the water intended for irrigation separately in the Mitidja alluvial aquifer.

Keywords

DRASTIC • geostatistics • GIS • Mitidja • sensitivity • water pollution

1. Introduction

In recent decades, droughts have disrupted the supply of drinking water and water intended for irrigation and industry, leading to excessive exploitation and increased demand for groundwater, which is often non-renewable or already polluted. These resources are both economically significant and environmentally fragile, requiring careful management and preservation. Surface and groundwater resources are continuously polluted by urban, agricultural, industrial, and accidental sources, providing a permanent risk of resource depletion. For their sustainability in terms of quantity and quality, their conservation and protection are required or even mandated [Djoudar and Toubal 2012a].

Algeria has experienced much higher than normal monthly average temperatures in recent years, with heatwaves in 2018 and the daily maximum surface air temperatures of 49°C for July 2023 [Copernicus 2023]. In addition, the current state of coastal aquifers in Algeria and the recent developments affecting them indicate that the significant deficits observed (due to the conflict between demand and resources) will increase [Haouchine et al. 2016]. Many researchers have also studied this issue [e.g. Benziada 1994, Djabri et al. 2003, Hadjoudj 2008, Drouiche 2012, Djoudar and Toubal 2014, Guendouz and Moula 2017, Aziez 2020, Medjdoub Leulmi 2021, Tachi et al. 2023, Ikhlef et al. 2024, Benouara et al. 2024]. The risk of depletion is superimposed on the qualitative degradation of the resource, essentially the risk of marine intrusion (where some aquifers are already abandoned), as well as anthropogenic pollution caused by agricultural activities (92% of the samples analyzed on the Mitidja aquifer exceed the maximum NO_3^- concentration allowed for the DWS), and industrial (where 250,000 m^3 of wastewater are discharged daily into the El Harrach river) [Haouchine et al. 2016]. According to Ouchene et al. [2018], the coastal zone alone accounts for nearly 44% of the population in the northern part of the country and almost half of the urban population, most of which is concentrated in the metropolitan area of Algiers.

The aim of the study is to highlight the vulnerability and sensitivity of groundwater (Mitidja) to contamination, providing a decision-support tool based on updated, revised, and recent data, as well as on unconventional techniques as geostatistics.

In order to carry out this work, the sensitivity indexing of alluvial aquifers will be combined with the DRASTIC parametric model [Aller et al. 1987] and the geographic information systems (GIS). The used indexing method was proposed by Pusatli et al. [2007]. This method was first applied to the Menderes aquifer in Turkey in 2007, then to the Cheba Mloulech aquifer in Tunisia by Saidi et al. [2009], and for the first time in Algeria by Djoudar and Toubal [2012b] and by Djoudar [2014], in the Mitidja specifically. This study is an update of the vulnerability assessment, using data from chemical groundwater analyses and piezometric in 2018, collected by National Water Resources Agency [NWRA]. The aim of the study is to provide an overview of the evolution of the vulnerability and sensitivity of groundwater in the Mitidja aquifer. The method will make it possible to consider separately the water intended for DWS and the water intended for irrigation. The application results from 2018 will be the subject of a comparative approach with the results of 2010, obtained by Djoudar [2014].

2. Methodology

This research has two parts: the determination of the sensitivity index to water pollution (SI) and the assessment of the water vulnerability index (IV) to pollution using the DRASTIC method. In fact, after the introduction of the concept of aquifer pollution vulnerability [Margat 1968], several groundwater vulnerability assessment methods have been developed and applied to different contexts in order to achieve the most adequate vulnerability maps for a given site. However, although different methods often result in significantly different vulnerability maps, there are some methods that can be applied to the aquifers, such as the DRASTIC parametric system [Guastaldi et al. 2014]. In order to optimize the use of both approaches and to have a better evaluation of the vulnerability values, the geostatistical approach was used for analyzing all the studied parameters. The study of the Mitidja aquifer area was divided into square meshes measuring 100 × 100 m, totaling 130,441 meshes and covering an area of 1,314 km². This step relied on the combination of geostatistics and geographic information systems to model and estimate the phenomenon in each cell of the studied area, taking into account its structure and spatial correlation, obtaining optimal estimates.

An in-depth preliminary geostatistical analysis of the experimental data is required in order to clearly identify the characteristics of these data, as well as to describe and model the spatial structure of the variable under study. This allows for the creation of statistically robust maps through kriging and quantifying of sample uncertainties using simulations to assess associated risks [Guastaldi and Del Frate 2012]. These analyses then allow the user to identify and process data anomalies and possible anisotropic conditions by using appropriate statistical representations such as variograms [Djoudar et al. 2019], coupled with map representations performed by QGIS version 2.18.24.The existing multidisciplinary data (geological, structural, geophysical, hydrogeological and hydrochemical) of the study area were processed by using the ISATIS 7.0 software [Geovariances 2007], to improve their quality (statistical study, outliers, variography analysis and data validation). The geostatistical approach allowed us to calculate kriged maps of chemical elements and the quality index (QI) of drinking water supply (DWS) and irrigation.

2.1. Evaluation of the water pollution vulnerability index using the DRASTIC method

DRASTIC is a standardized method for assessing and mapping the vulnerability of groundwater, regardless of the type of pollutant, which takes into account most of the hydrogeological factors that affect and control groundwater flow [Aller et al. 1987].

The DRASTIC index (IV) is based on the evaluation of seven parameters. Each parameter is assigned a relative weight, with a value between 1 and 5, according to its importance in the process of mitigation of contaminants. The weight of a main parameter is 5, while the weight of a parameter with less impact on the fate of pollutants is 1. Each parameter is then assigned a value that can vary from 1 to 10, from the least to the most vulnerable state (Equation 1).

$$\text{DRASTIC Index} = (Dc \cdot Dp) + (Rc \cdot Rp) + (Ac \cdot Ap) + (Sc \cdot Sp) + \\ + (Tc \cdot Tp) + (Ic \cdot Ip) + (Cc \cdot Cp) \tag{1}$$

where:
- C – rates of the considered parameters,
- Dc – rate of parameter,
- D – its weight.

The DRASTIC vulnerability index provides a way of assessing the degree to which the aquifer system is at risk of contamination from surface pollution. This vulnerability increases as the index value increases, from a minimum value of 23 to a maximum of 226. It can only be assessed by a comparative analysis of different sites or hydrogeological units.

2.2. Determination of water pollution sensitivity index (SI)

The results of the DRASTIC vulnerability index (IV) and water quality indexes (IQ) [Pusatli et al. 2007] are taken into account in the calculation, namely (Equation 2):

$$\text{SI} = \text{IV} \cdot \text{IQ} \tag{2}$$

It is assumed that when the DRASTIC method is applied at the regional level, the initial sources of pollution spread from the surface into the environment, and the quality of the pollutants does not affect the vulnerability. The indexing of the sensitivity of the quality of irrigation water and drinking water supply takes into account the classification of waters into five groups with respect to each concentration of ions, very good (I), good (II), usable (III), usable with caution (IV) and harmful (V). The limit values for each category of the parameters considered are listed in Tables 1 and 2. The quality index for a given location was calculated according to the following formula (3):

$$\text{IQ} = \sum_{i}^{n} (C_i)^2 \tag{3}$$

where the sum is generally considered as the quality parameter (of the ions), and C_i – the class of parameter i (Ion). The integer value for a given position ranges between 1 and 5. Using of the square of the C_i concentration per ion can enhance the impact of low-quality levels [Pusatli et al. 2007].

Table 1. Classification of irrigation water

Parameters	Limits used for irrigation water				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (μS/cm)	0–250	250–750	750–2000	2000–3000	> 3000
Cl^- (mg/l)	0–142	142–249	249–426	426–710	> 710
NO_3^- (mg/l)	0–10	10–30	30–50	50–100	> 100
SO_4^{2-} (mg/l)	0–192	192–336	336–575	576–960	> 960
Na^+ (mg/l)	0–69	69–200	200–252		> 252

Source: Pusatli et al. [2007]

Table 2. Classification of drinking water

Parameters	Limits used for drinking water				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (μS/cm)	0–180	180–400	400–2000	2000–3000	> 3000
Cl^- (mg/l)	0–25	25–200			> 200
NO_3^- (mg/l)	0–10	10–25	25–50		> 50
SO_4^{2-} (mg/l)	0–25	25–250			> 250
Na^+ (mg/l)	0–20	20–200			> 200

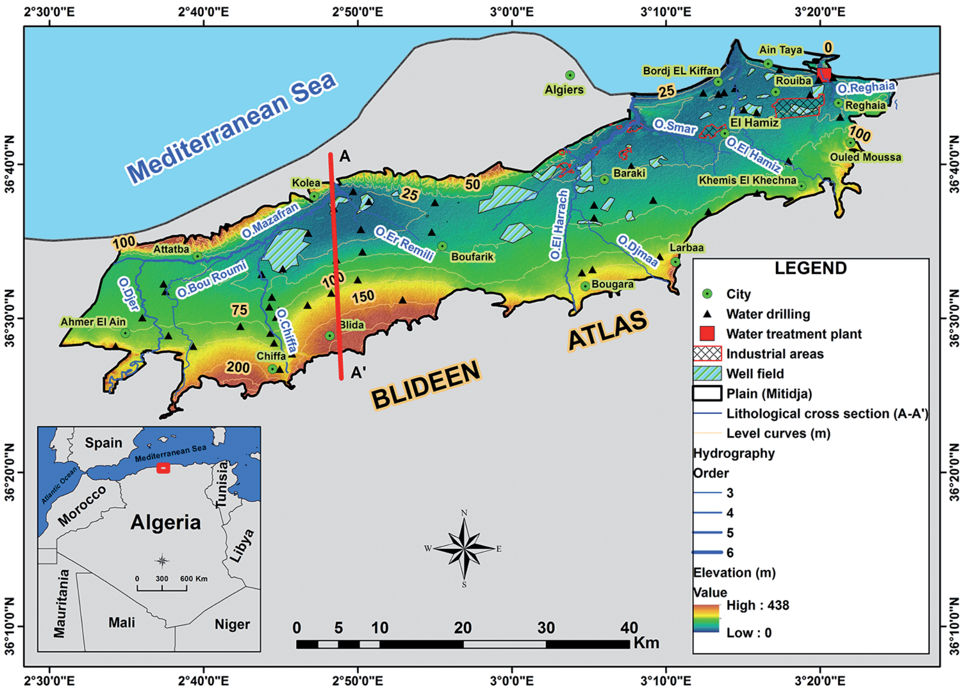
Source: Lenntech [2008], Saidi et al. [2009]

3. Overview of physical environment

Mitidja is located in north central Algeria. It is part of the large Algerian coastal basin, coded 02 by the NWRA. Due to its geographical location and agricultural use, it is a strategic sublittoral plain.

The Mitidja plain is located to the south of Algiers. It includes the areas of Algiers, Boumerdes, Tipaza and Blida. It has a WSW–ENE orientation, with an average altitude of 100 m. It starts from the Boudouaou river in the east and ends at the Menacer basin in the west, with an area of 1314 km^2, a length of about 100 km, and a width of 15–20 km (Fig. 1).

The eastern end of the plain is open to the sea, while the Sahel hills at the western end are connected to the Chenoa Mountains (905 m above sea level). The plain is divided into four sub-basins (Hamiz, Harrach, Mazafran and Nador), with a total area estimated at 3544 km^2. The water is drained from the south to the north by a dense water system. All the tributaries of these wadis originate at the top of the Altlas Blidéen, and their general direction of flow is south-north.



Source: Authors' own study

Fig. 1. Geographical location of the study area

The highest flows are recorded in the Mazafran Wadi, the largest of which is the Mazafran river, with a length of 65 km. The Mazafran river basin covers an area of 1,900 km^2. It includes three groups of watercourses: Oued Djer, Oued Bou Roumi and Oued Chiffa. A hydrological study carried out between 1971 and 2004 showed that the average rainfall was 607 mm; the infiltrated water was 35 mm, accounting for 6% of the rainfall, while the run-off was 51 mm, representing 9% of the rainfall. This is due to the dominance of the geomorphic features and the impermeable layers of the basin, conducive to runoff. The Martonne drought index of the study area is equal to 16, in a semi-arid climate [Djoudar 2014].

Given its agricultural nature, characterized by the existence of an area of high agronomic value, Mitidja is considered one of the most important agricultural complexes in the PAC zone [PAC 2004].

According to PAC [2004], the urbanization of agricultural land in Mitidja stopped between 1962 and 1980. However, since the 1980s onwards, the urbanization of Mitidja began with the construction of houses on less appropriate land (Bouzaréah, El Biar, Ben

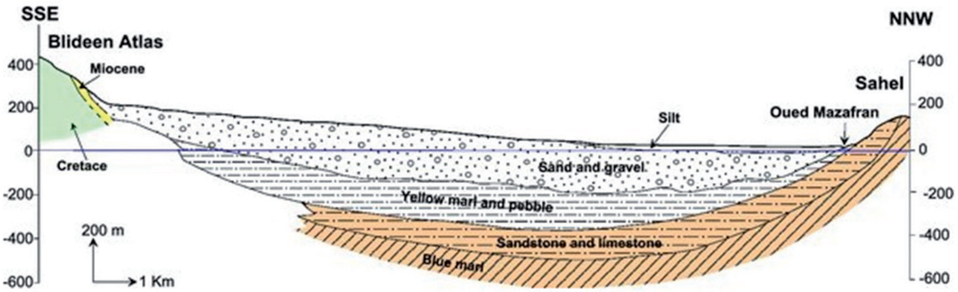
Aknoun, etc.), but very quickly the construction zones extended to the entire coastal area.

Most of the industrial activity is concentrated in the central and eastern part of the plain (Arbaa, Blida, El Harrach, Boufarik), including two industrial centers in Rouiba and Reghaia. Mitidja plain is a Neogene basin in Algeria, where several geological surveys have been carried out mainly based on the work of Glangeaud [1952], Ayme [1956], Durand Delga [1969] and Bennie and Partner [1983].

At the hydrogeological level, there are two distinct aquifers:

- The Astian, formed by limestone and sandstone of continental origin.
- The Quaternary layer is mainly composed of coarse alluvium (gravel, pebbles, silt and clay, in varying amounts).

The latter is very thick in the center (100–200 m) and becomes thinner towards the edges. The two aquifers are separated throughout the plain by semi permeable yellow marl of the El Harrach formation (Villafranchen), except in the Rouiba pocket where the two aquifers meet. These two aquifers are located on an impermeable basement and are usually composed of grey and blue marls of Plaisancian period (Fig. 2).



Source: modified from Bouderbala [2019]

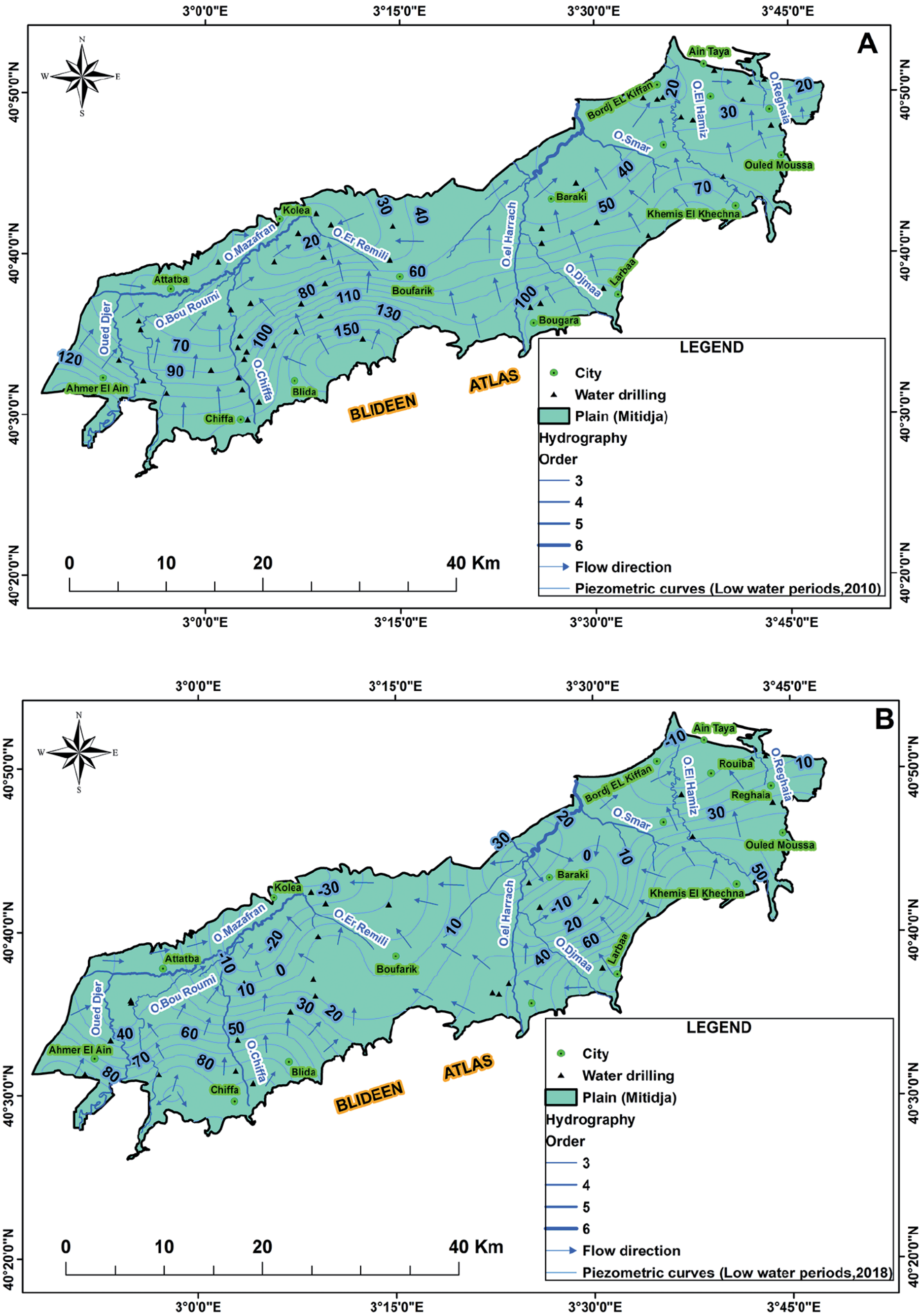
Fig. 2. Cross-sectional of the Mitidja aquifer

In the present study, only the Quaternary formation will be the subject of the study of the vulnerability and sensitivity of the groundwater in the Mitidja alluvial aquifer.

To better understand of the hydrodynamic behavior of the Mitidja alluvial aquifer reservoir, we used the interpretation of the 2018 low water piezometric map (B), the results of which were compared with those of 2010 (A) (Fig. 3).

By analyzing the piezometric maps (Figs. 3A and B), the following conclusions can be drawn:

- The piezometric values decrease from south to north, indicating the general flow of the aquifer towards the sea, while on the eastern side of the study area, the flow was reversed in previous works, highlighting the seawater intrusion first mentioned by [Mania 1985], and also attested by many other authors also [e.g. Djoudar 1993], [Haouchine et al. 2016]. It is worth noting that this situation continues to exist be-



Source: A. Djoudar [2014], B. Authors' own study [2018]

Fig. 3. Piezometric maps of low water periods in the alluvial aquifer of Mitidja from 2010–2018: A. 2010, B. 2018

cause NWRA technicians no longer measure the coastal area on the side of Bordj El Kiffan. As a result, the lack of a coastal survey means that it is not shown on either map.

- East of Blida town, the SSE-NNW groundwater line connects the Boufarik well field and then the Mazafran 1 well field to the north.
- Two converging flow depressions are observed; to the east, the well fields of, Baraki, three cellars, Oued Adda and Stamboul to the west, on the side of Mazafran 1 and 2, Blida, Boufarik, well fields.
- The map of low water levels in 2018 shows a more pronounced drawdown than in 2010 with a depression reaching a depth of 0 m. This indicates that the scarcity of rainfall is leading to over-exploitation of groundwater.
- The hydraulic gradient is low, around 0.005 in the whole northern aquifer zone, while in the south, the gradient is higher, ranging from 0.016 to 0.023.

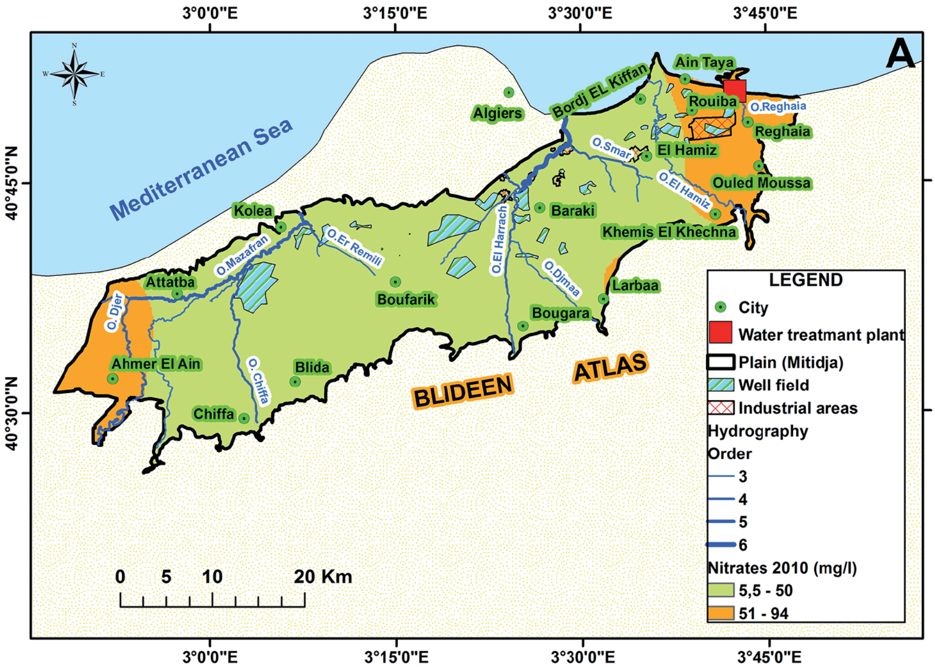
The hydrochemical method allows us to determine the nitrate pollution in the west and the east of the study area in 2010. Unfortunately, the nitrate pollution in the middle and east of the study area increased in 2018, reaching over 50 mg/l (Fig. 4).

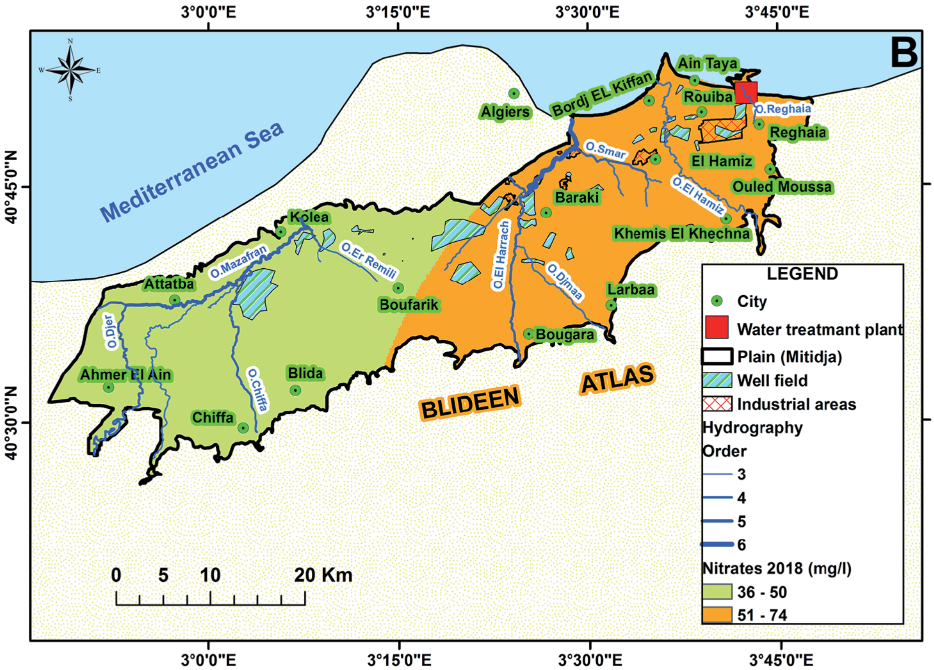
According to Gouaidia [2012], chloride ion has different characteristics from other elements, is not adsorbed by geological structures, is not easily combined with chemical elements and maintains high mobility. It is a good indicator of pollution (Table 3).

Table 3. Descriptive statistical parameters of the variables, 2010/2018

Year	Parameters	Variables				
		EC (µS/cm)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Na^+ (mg/l)
(2010/2018)	Minimum	599/560	33/36	1.3/17	15/0.5	12/19
	Maximum	2900/2415	400/490.1	108.7/96.5	407.5/419.5	190/324
	Mean	1404.2/1416	135.2/145.9	35.3/51.3	163.5/167.1	73.9/97.7
	Median	1400/1302	130/106	26.4/50.5	175/165	64/85
	Standard deviation	607.2/579.6	86.5/109.7	26.6/22.8	97.5/111.2	49.3/74.3
	Coefficient of variation	0.43/0.41	0.64/0.75	0.75/0.44	0.60/0.66	0.67/0.76
	Skewness coefficient	0.31/0.10	0.95/1.28	1.02/0.19	0.33/0.39	0.61/1.16

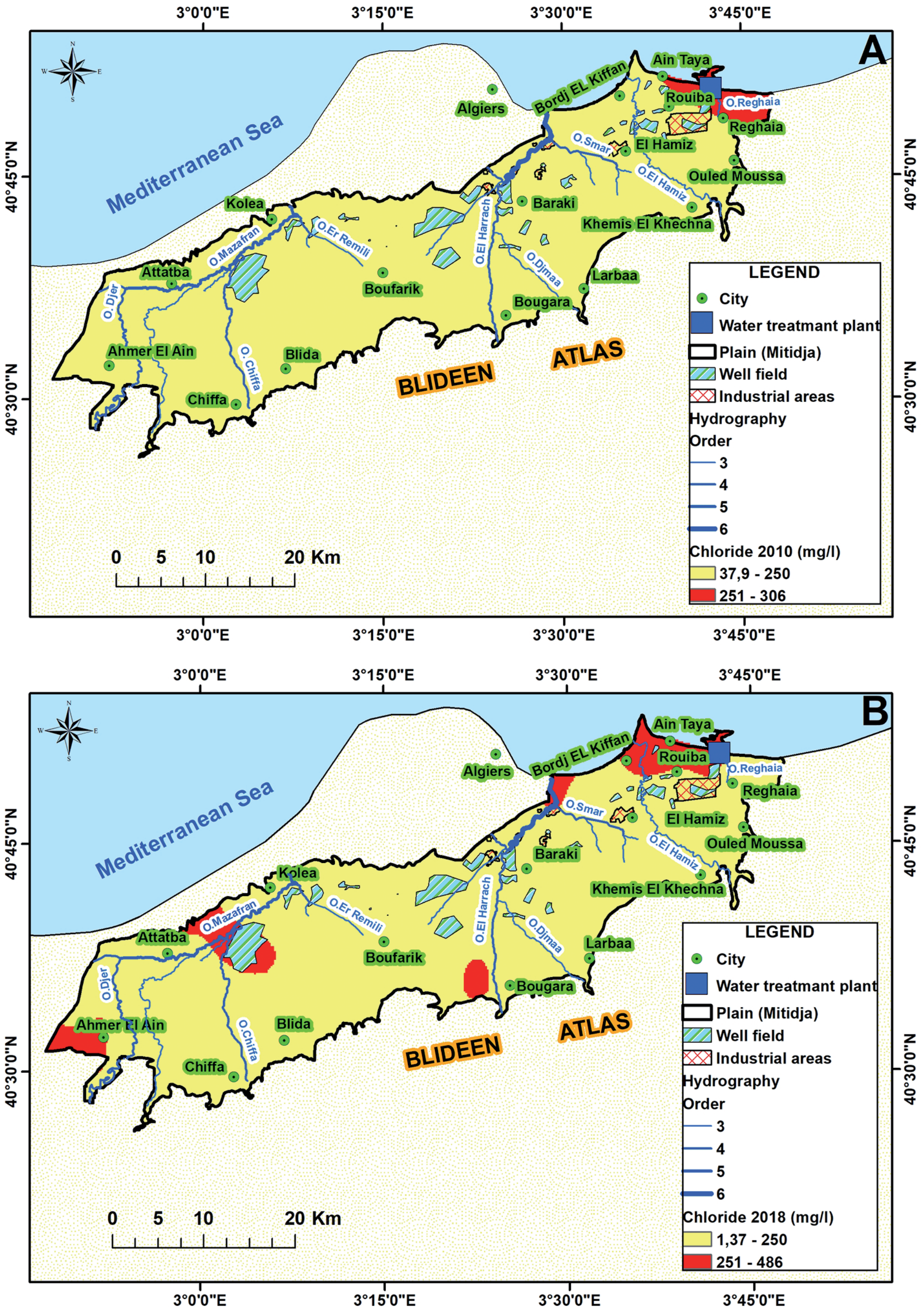
In 2010, the recorded concentration showed that the significant value was over 300 mg/l, far exceeding the World Health Organization [WHO 2011] drinking water standard of 250 mg/l, and the average value of the low water level was 135.2 mg/l. Areas of high concentrations were observed on the northeastern coast of the study area. The phenomenon of seawater intrusion persists with the advance of the salt water into the continent, confirming the previous interpretation of the piezometric maps.





Source: A. modified from Djoudar [2014], B. Authors' own study [2018]

Fig. 4. Map of Nitrates in low water period: A. 2010, B. 2018



Source: A. modified from Djoudar [2014], B. Authors' own study [2018]

Fig. 5. Map of chlorides in low water period: A. 2010, B. 2018

In 2018, the areas with chloride concentrations higher than the standards recommended by the WHO continue to be distributed in the same areas as in 2010, with the appearance of new beaches, namely, north of the Algiers city side and south of the communities of Bouinan and Chebli, upstream of the west of El Harrach, west of Bougara. The western zone on both sides of the Oued Mazafran is also characterized by high concentrations and the last is Ahmer El Ain at the westernmost end (Fig. 5). This increase in values can be explained by the leaching of eruptive formations and clay alluvium; they could also have several origins:

- Quaternary clay alluvium.
- Sewage discharged into the plain.
- The marls of the El Harrach formation.
- Marine intrusion.

4. Results and discussion

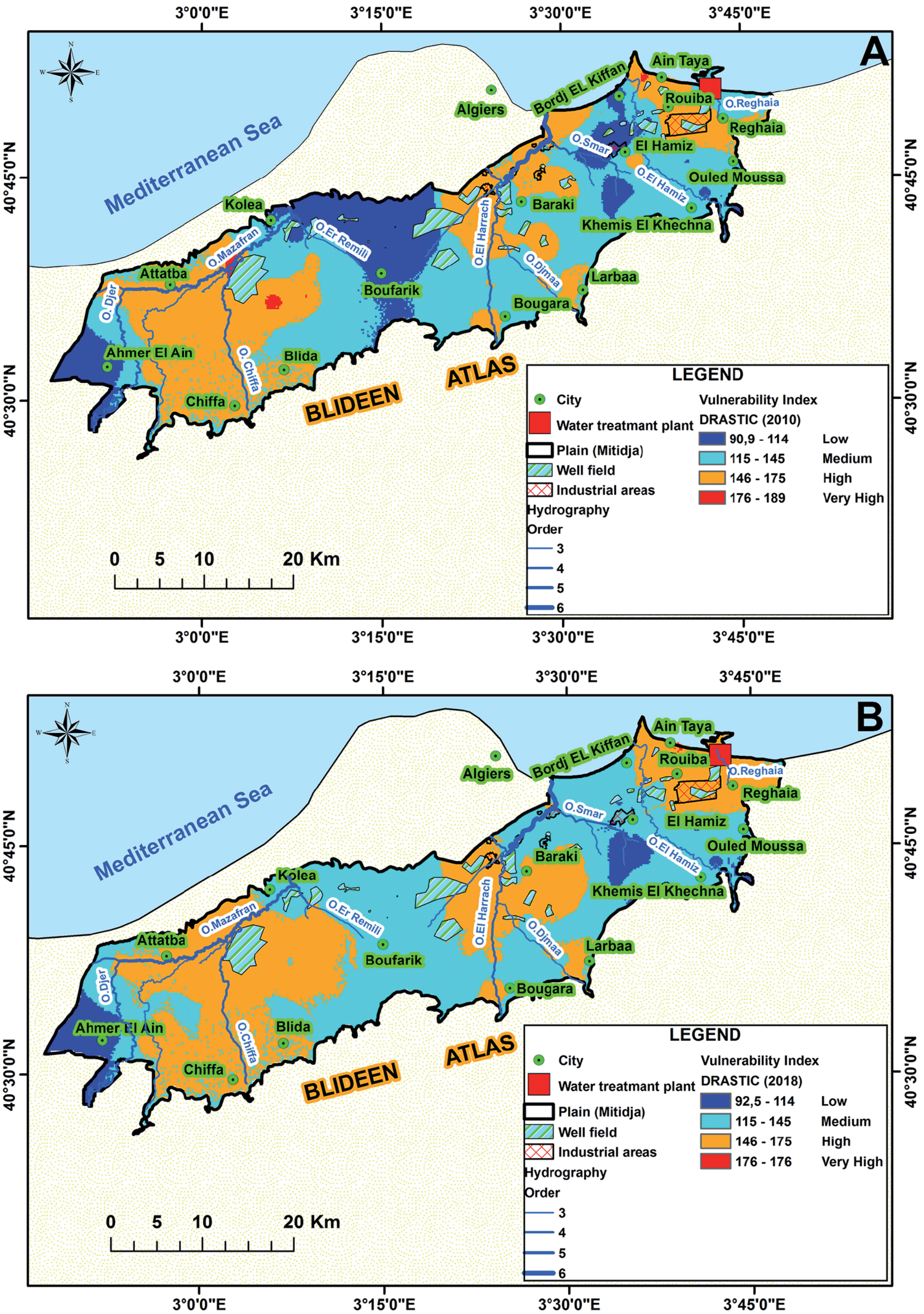
4.1. DRASTIC maps

The 2010 DRASTIC map indicates that approximately 44% of the region is moderately vulnerable, while nearly 39% is highly vulnerable. Since the vulnerability index of most of the study areas is between 114 and 175, these vulnerable areas are mainly located in sensitive areas. Specifically, in the northern supply region (Bourelet Sahelian), in the south (alluvial cones of the Blideen Atlas) and along the river banks (Wade-aquifer relationship) (Fig. 6).

On the other hand, the 2018 DRASTIC map indicates that about 56% of the total area is classified as medium vulnerability. Although the scope of high vulnerability has expanded and damaged low vulnerability areas, high vulnerability areas cover nearly 45% of the total area. This is because the vulnerability index of most of the study areas is between 146 and 175.

Most of these vulnerable areas are mainly located in sensitive areas: in the northern supply area (Bourelet Sahelian Rouiba and Ain Taya), the Atlas dejection cones Larbaa, Bougara, Blida, and Chiffa; and at the level of the banks of the Oueds in the south. According to the lithology of the saturated zone, these areas are composed of gravel and sand with a low clay content. Their hydraulic conductivity ranges from $4.720 \cdot 10^{-4}$ m/s to $9.44 \cdot 10^{-4}$ m/s, and can exceed $9.44 \cdot 10^{-4}$ m/s at any point. They are located in the Baraki well field in the center and in the east of Hamiz. Therefore, in most parts of the west, in the south of Chifa Blida, Attatba and Koléa, large beaches can be seen along Mazafran and Oued Chifa.

Notably, areas classified as having low vulnerability (92.5 to 114) in 2010 transitioned to medium vulnerability (115 to 145) in 2018, mainly in the center of Boufarik and to the east of the study area. They are composed of alternating gravel, sandy clays, marls and clayey gravels with a hydraulic conductivity varying from $3.30 \cdot 10^{-4}$ m/s – $4.72 \cdot 10^{-4}$ m/s. It covers an area of 722.7 km^2 of the Mitidja alluvial aquifer.



Source: A. modified from Djoudar [2014], B. Authors' own study [2018]

Fig. 6. Vulnerability index DRASTIC maps of the Mitidja alluvial aquifer: A. 2010, B. 2018

4.2. Water quality index

Chemical analysis data from the 2018 dry season were used to calculate the water quality index for drinking water supply (IQ DWS) and the irrigation water quality index (IQ irrigation) (Table 3). This is the period when the groundwater is in high demand by farmers.

Only chemical elements with high concentrations are taken into account, namely: electrical conductivity (EC), chloride (Cl^-), sodium (Na^+), nitrates (NO_3^-) and sulphates (SO_4^{2-}).

For this purpose, we have assigned an integer (1 to 5) to each concentration C_i of an element i. defined in Tables 1 (irrigation water) and 2 (drinking water DWS).

As a result, two groundwater quality maps were produced for the year 2018: water intended for DWS and water intended for irrigation. These two maps will be compared with the 2010 map.

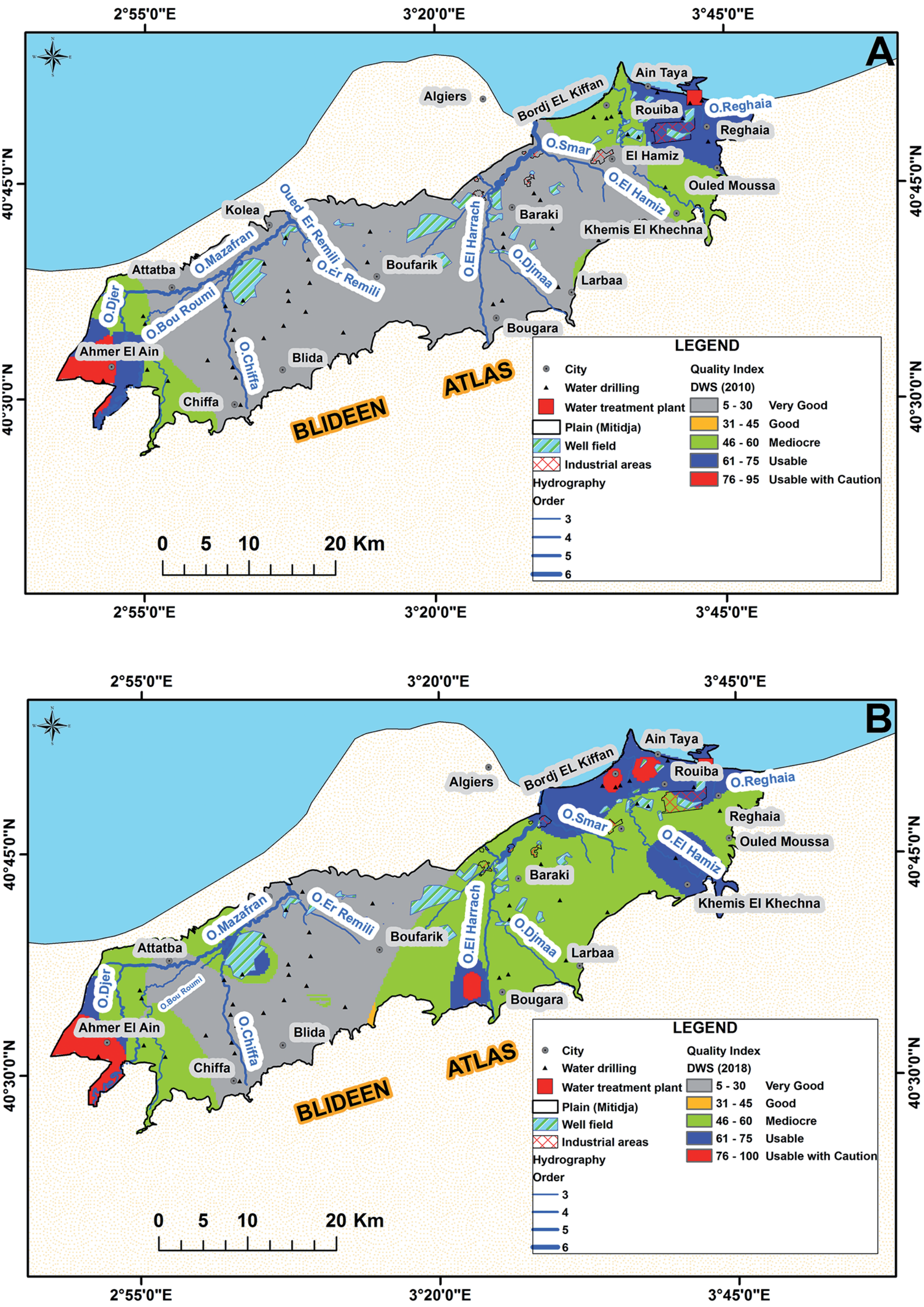
The map based on the thematic analysis of chemical quality attributes (IQ) (Fig. 7) shows that this parameter is no longer as reassuring as it was in 2010.

Despite the high-level degree of industrialization in the Mitidja plain, the chemical quality of groundwater is very good in most the areas studied. As a result, the water quality map, IQDWS 2018, is characterized by a spreading of areas of average quality to the detriment of areas with good and very good quality, particularly in the central and eastern part of the study area. This confirms the observation made by Khous et al. [2019], where they state that the quality of waters is also characterized by the presence of nitrate, which can be reasonably attributed to the use of fertilizers in the agricultural area.

The IQDWS 2018 map reveals a new usable quality zone that can be adopted with caution upstream of the El Harrach river. This may be worrying, considering that this area constitutes a groundwater recharge area where the height of the penetrating water layer is greater than 25cm/year. It also receives rainwater, water from the Blideen Massif and water from the wadi by infiltration [Djoudar 2014]. Thus, the waters of the aquifer can be used with caution, especially in the industrialized areas of Mitidja. As for the poor-quality waters in 2010 and 2018, they are still located in the westernmost part on the side of Ahmer El Ain and the northeasternmost on the side of Reghaia, due to industrial discharges.

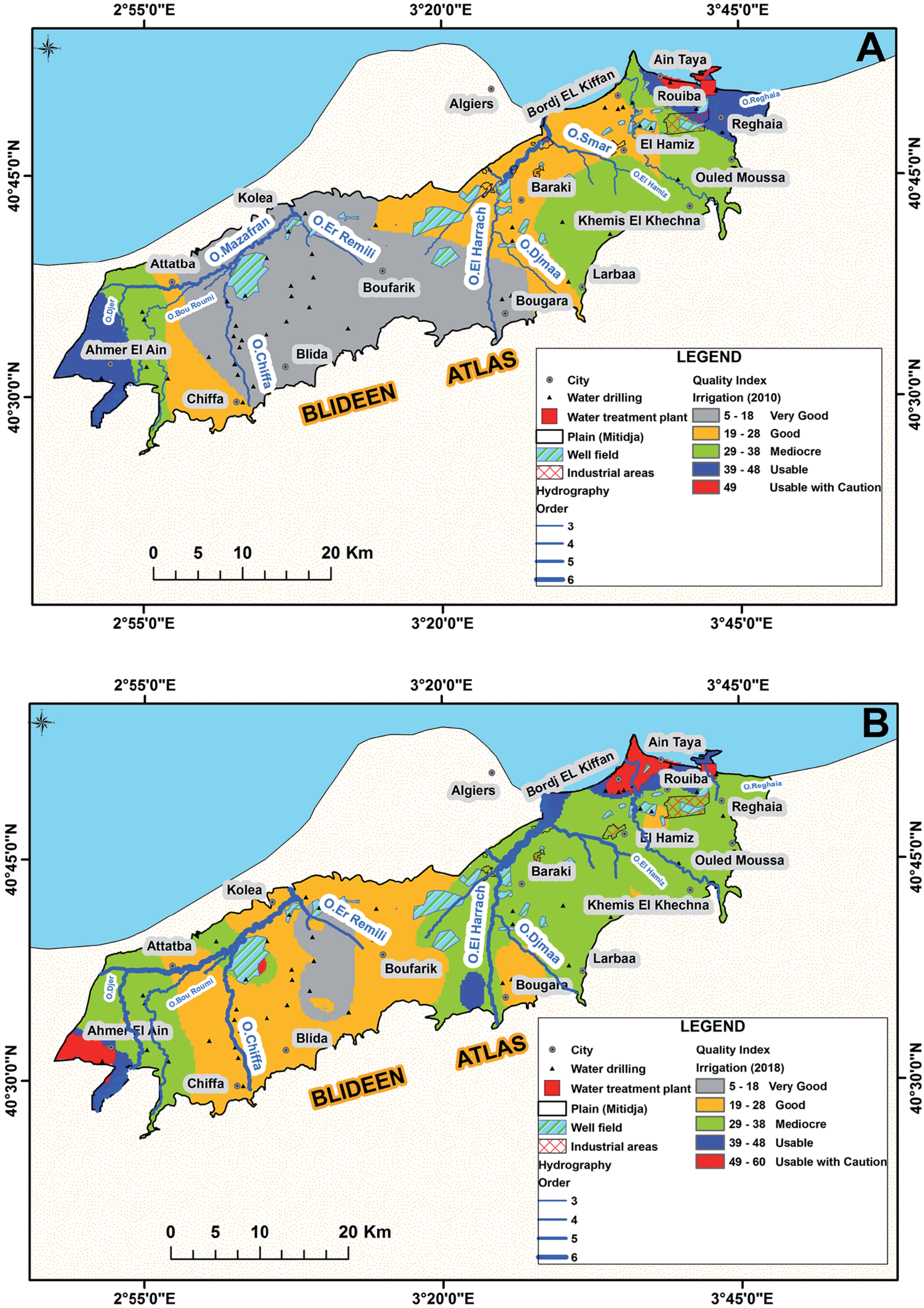
The irrigation water chemical quality index maps (Fig. 8A and B) show an increase in water chemical quality degradation in 2018.

The difference between the two maps lies in the eastern and central Mitidja. The IQ irrigation map in 2018 shows that the situation of poor water quality is getting worse and worse, deteriorating the good water quality. Unfortunately, the very good quality, that prevailed in 2010, has given way to water categorized as good quality in the western zone near Ahmer El Ain and the far north-east near Ain Taya with a spread of average quality water, which should be used with caution. This process is explained by urbanization and massive industrialization of agricultural land and the increase in water demand, which has led to the continuous problem of seawater intrusion problem in the coastal zone Bordej El Kiffan for 30 years, as previously mentioned.



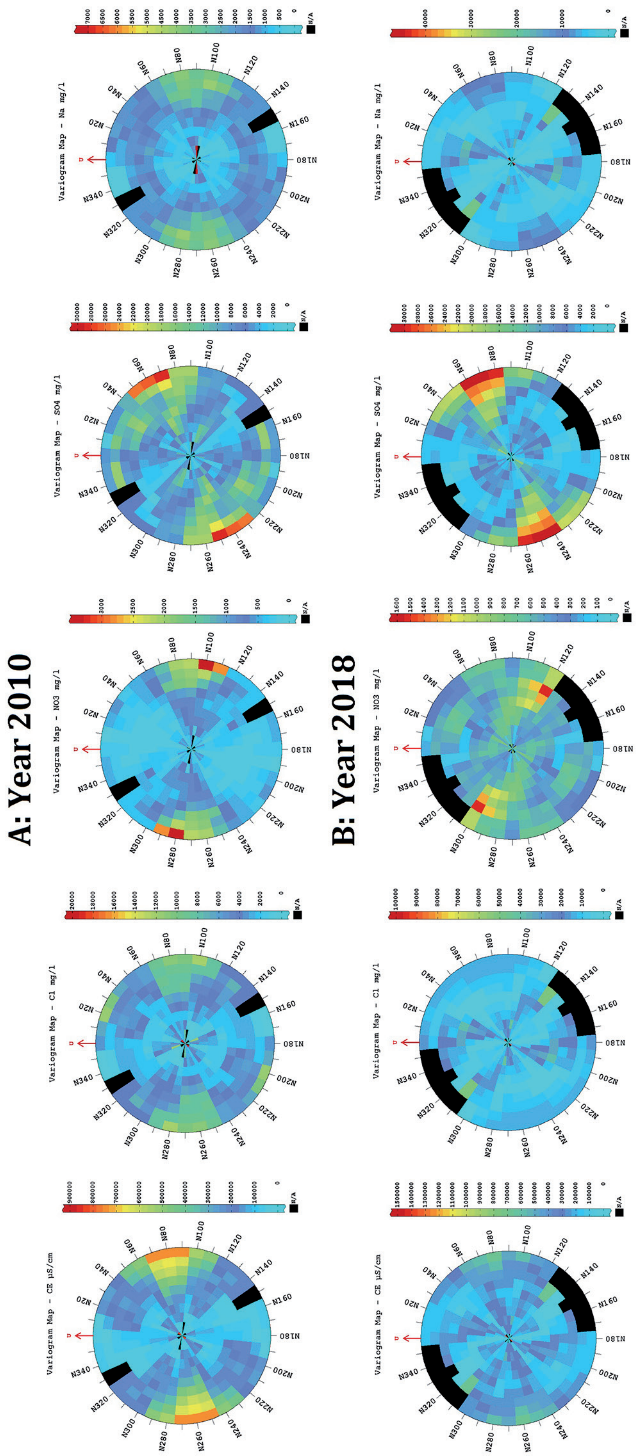
Source: Authors' own study

Fig. 7. IQ map of water intended for DWS: A. 2010, B. 2018



Source: Authors' own study

Fig. 8. IQ map of water intended for irrigation: A. 2010, B. 2018



Source: Authors' own study

Fig. 9. Surface variograms of the variables (EC, Cl^-, NO_3^-, SO_4^{-2} and Na^+)

In this regard, and in order to understand the current state of groundwater quality in the Mitidja alluvial aquifer, the study of the semi-variograms of the different chemical elements analyzed was carried out to highlight the evolution of groundwater contamination from 2010 to 2018, especially in the central and eastern area of the study area.

The possible presence of an anisotropic structure of the spatial variability was checked by mapping the directional variability in the plane (variogram map) and then analyzing its span according to the spatial direction. However, even if some variables could show some kind of anisotropy, the resulting semi-variograms were too erratic, so the isotropic condition was preferred (Fig. 9).

This paper presents a calculation of the best omnidirectional experimental semi-variogram (ESV) of EC variable – its step length (lag distance) is 650 m and 12000 m: Cl^-, NO_3^-, SO_4^{-2} and Na^+ in 2010 and 2018. Their modeling is done by the Gaussian model function.

Table 4 shows the number and type of structures, the span in meters, the models applied to these experimental variable maps, and the cross validation to verify the robustness of the models.

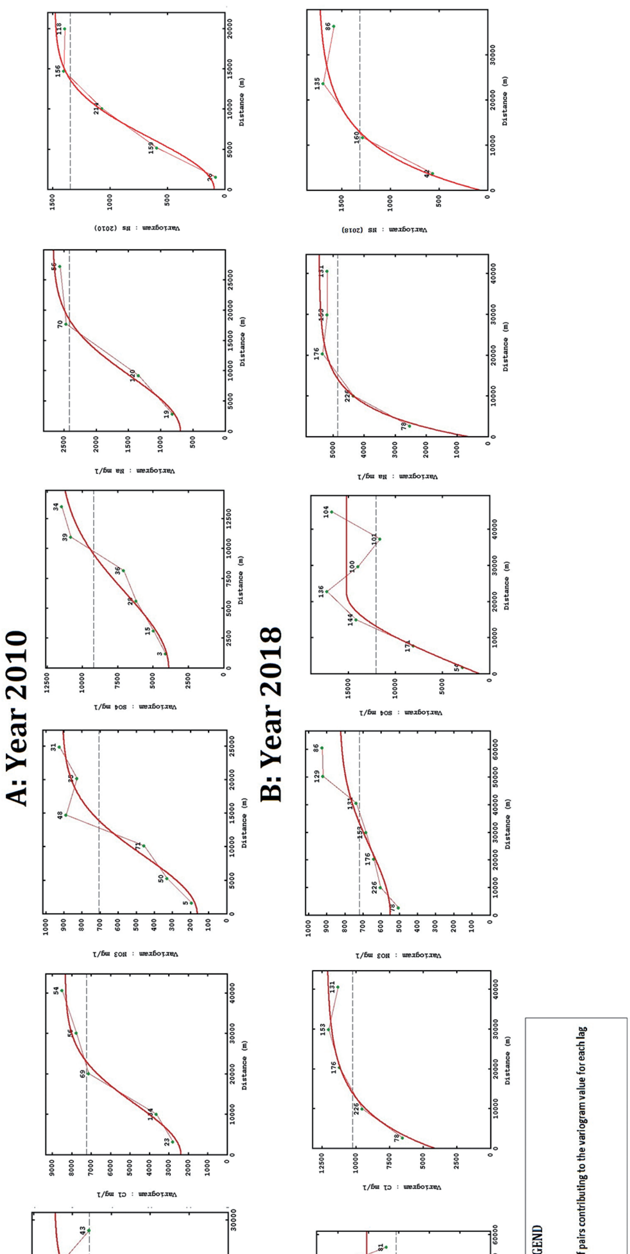
The results show that the model has a spherical variability. The exponential and Gaussian structures of all variables are well structured (Fig. 10). It appears that the standard error distribution is Gaussian, the mean standard error (MSE) is zero, and the standard error variance (VSE) is equal to the unit. This means that the model chosen is not too wrong. These models have been utilized for interpolating the variables by ordinary kriging, which has the advantage ensuring the minimum estimation variance [Laborde 2000].

4.3. Map of the IS sensitivity index of the Mitidja groundwater

After the mapping of the chemical composition of water intended for drinking water supply 'IQ. DWS' and for irrigation 'IQ Irrig', the water sensitivity index in each water point was calculated using formula (2). The DRASTIC value for each water point considered is multiplied by the value of the pollution water quality index obtained by formula (1) for the same water point considered. These spatial data were processed in the QGIS software in order to develop two 2018 sensitivity maps: a 'SI DWS' drinking water index map (Fig. 11) and 'SI Irrig' irrigation water sensitivity map (Fig. 12). These two maps will be compared to those produced by [Djoudar 2014].

4.3.1. Drinking water sensitivity index map

Figure 11 shows that in 2018, the medium-high sensitivity of the aquifers in the central and eastern parts of the study area changed, and the ultra-high sensitivity increased significantly, especially in the coastal areas between Bordj El Kiffan and Reghaia, including the entire Rouiba industrial zone in the easternmost part of the study area and the westernmost part of Ahmer El Ain.



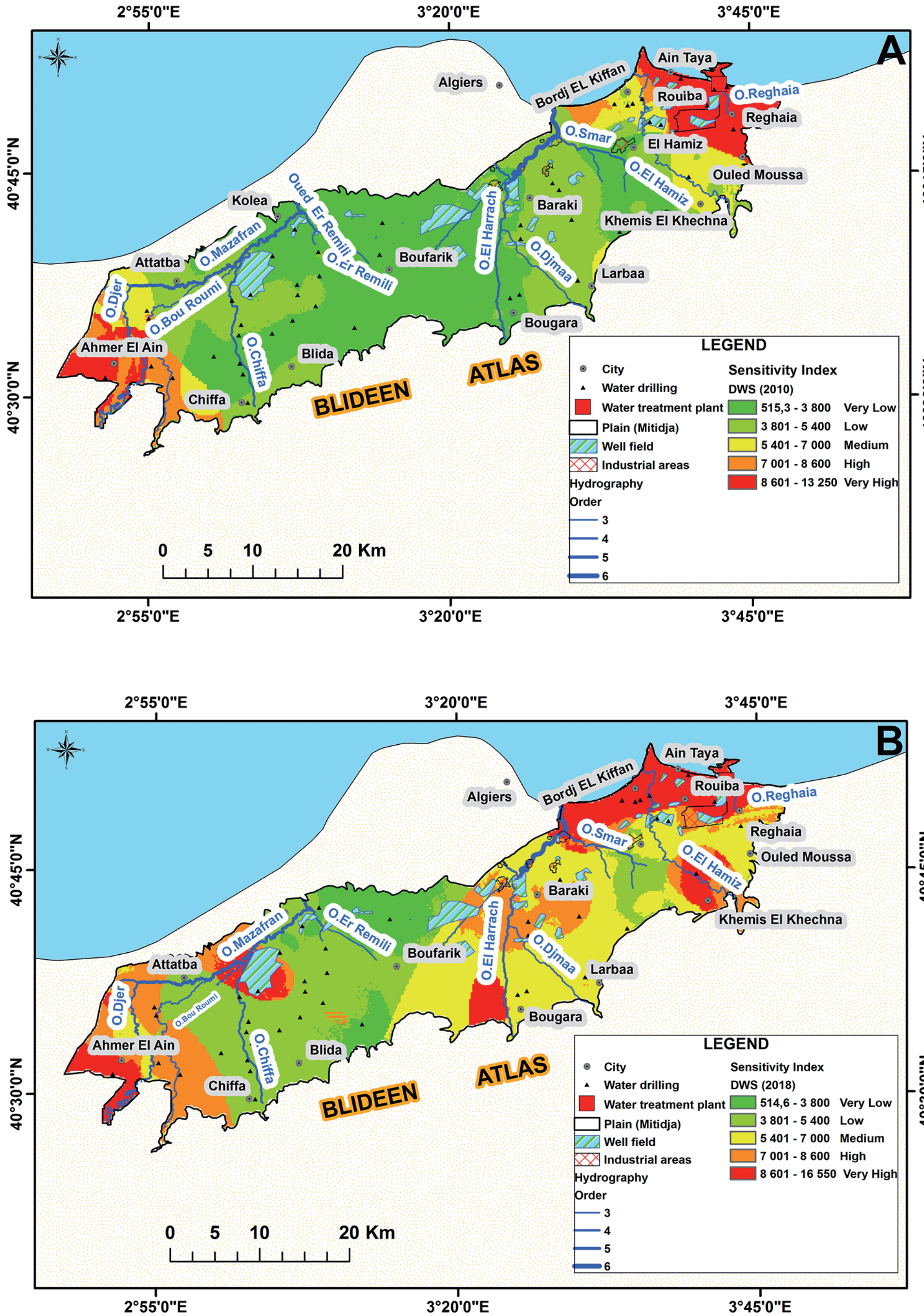
Source: Authors' own study

Fig. 10. Omnidirectional model for ESV

Table 4. Parameters of variogram modeling procedure (MSE: Mean of standardized errors, VSE: Variance of standardized errors)

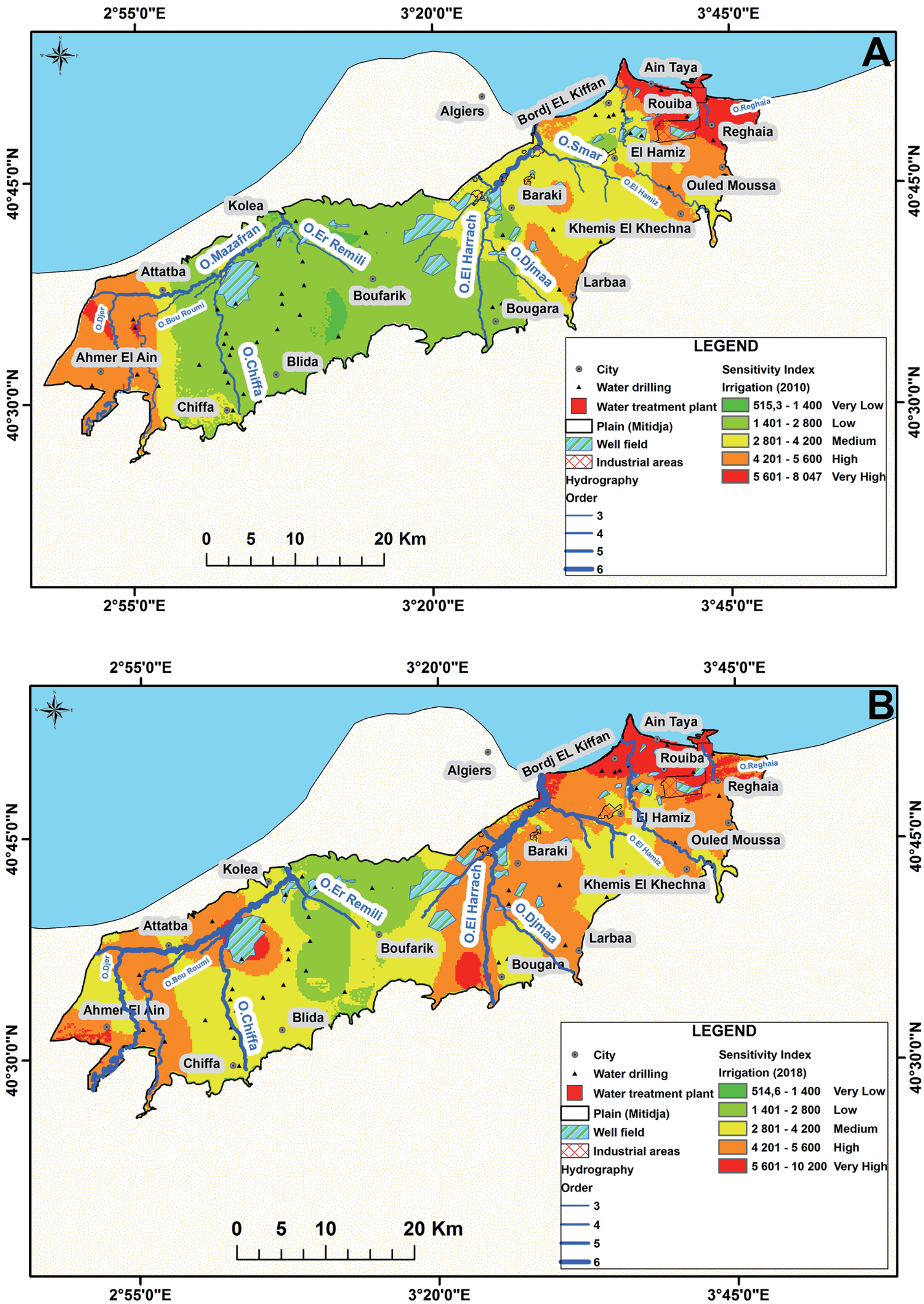
Variables	Year	Experimental Semi-Variogram Omnidirectional (ESV)		Number and type of structure		Range [m]	Sill	Cross-validation	
		Lag distance (m)	Number of lag distance					MSE	VSE
EC (µS/cm)	2010	700	5	1	Nugget Effect model	–	$6.5*10^4$	0.05	1.02
				2	Gaussian Model	22800	$3.8*10^5$		
CL^- (mg/l)		10000	5	1	Nugget Effect model	–	2384	0.06	1.15
				2	Gaussian Model	30600	5961		
NO_3^- (mg/l)		5000	6	1	Nugget Effect model	–	163.4	0.02	1.08
				2	Gaussian Model	21000	745.6		
SO_4^{-2} (mg/l)		650	12	1	Nugget Effect model	–	3998	0.03	1.04
				2	Gaussian Model	15400	7818		
Na^+ (mg/l)		9000	4	1	Nugget Effect model	–	694	0.04	1.03
				2	Gaussian Model	22300	1979		
Piezometric level (m)		5000	5	1	Nugget Effect model	–	92	0.08	0.95
				2	Gaussian Model	15400	13.88		
EC (µS/cm)	2018	8000	8	1	Nugget Effect model	–	$1.3*10^5$	0.02	1.04
				2	Gaussian Model	23500	$2.7*10^5$		
CL^- (mg/l)		10000	5	1	Nugget Effect model	–	41.49	0.003	1.26
				2	Exponential Model	29200	8037		

NO_3^- (mg/l)	2018	10000	7	1	Nugget Effect model	–	550	0.005	1.05
				2	Gaussian Model	59600	300		
SO_4^{-2} (mg/l)		7500	7	1	Nugget Effect model	–	1081	0.01	1.01
				2	Spherical Model	22460	$1.4*10^4$		
Na^+ (mg/l)		10000	5	1	Nugget Effect model	–	623	0.009	1.18
				1	Exponential Model	20320	4828		
Piezometric level (m)		12000	4	1	Nugget Effect model	–	74.3	0.06	0.98
				2	Exponential Model	28520	1673		



Source: Authors' own study

Fig. 11. Map of SI DWS: A. 2010, B. 2018



Source: Authors' own study

Fig. 12. Map of SI irrigation: A. 2010, B. 2018

Unfortunately, the low and very low sensitivity beaches that characterized the area from Attatba to Koléa in 2010 have disappeared, to the detriment of the high sensitivity areas surrounding the very high sensitivity area area in 2018. More worryingly, the first two highly sensitive areas around Bougara and Khemis el Khechna, which are recharge zones for the Mitidja aquifer, have appeared.

4.3.2. Irrigation water sensitivity index map

Figure 12 (A) shows that in 2010, the water quality was generally poor, and the sensitivity index 'SI irrig' exceeded 2800. Therefore, the sensitivity of these waters was very high in most parts of the study area.

This issue got even worse in 2018. The sensitivity index 'SI irrig' is greater than 4200 in the most of the high sensitivity and very high sensitivity study areas, as shown in Figure 12 (B). However, the areas of low sensitivity in the central area between Boufarik and Blida decreased in 2018 compared to 2010, with the complete disappearance of the very low sensitivity areas. This confirms that the primary source of anthropogenic pollution is the leaching of layers in contact with the groundwater within the study area. In order to confirm the results of the study, we compared the values of the vulnerability indices DRASTIC 2010 and DRASTIC 2018, as well as the sensitivity index 2010 and 2018 (Table 5).

Table 5 indicates that the vulnerability and sensitivity of groundwater in Mitidja has changed and deteriorated in 2018 compared to 2010. In fact, this index was lower in 2010, since it was equal to 45.43% of the total area of drinking water in the study area, only 8.25% of the total area, compared to 9.53% in 2010 and 28.06% in 2018. Therefore, the index is increasing, since it is equal to 5.34% and 9.87% in 2010, rising up to 19.77% and 15.78% in 2018.

Table 5. Comparison of DRASTIC indexes 2010–2018 and sensitivity indexes 2010–2018

Vulnerability index (VI, %)				
Years	**Low**	**Medium**	**High**	**Very High**
2010	17.08	44	38.34	0.56
2018	0.003	55.35	44.62	0.03

Sensitivity index (SI, %)						
Years	**Type**	**Very Low**	**Low**	**Medium**	**High**	**Very High**
2010	DWS	45.43	29.83	9.53	5.34	9.87
	Irrigation	1.80	47.26	27.21	18.20	5.53
2018	DWS	8.25	28.13	28.06	19.77	15.78
	Irrigation	0.05	12.21	37.19	42.01	8.55

The change of sensitivity of irrigation water is almost the same as that of DWS water. In fact, the IS medium sensitivity index and high sensitivity index increased from 27.21% and 18.2% to 37.19% and 42.01%, respectively, indicating that the groundwater pollution in the study area has increased alarmingly.

The vulnerability and sensitivity level map of the Mitidja river alluvial aquifer to potential pollution was created using the method developed by Pusatli et al. [2007]. It provides a groundwater sensitivity map tool for decision-making by water resource and environmental managers. The results are very interesting, namely the chemical water quality and its sensitivity index are plotted by considering DWS and irrigation water of the Mitidja alluvium aquifer separately.

5. Conclusion

According to the obtained results, the DRASTIC model and the sensitivity index method based on the geostatistical approach to define (drinking water and irrigation water) have been combined to carry out a comprehensive study of groundwater resources in the alluvial aquifer of Mitidja.

In this study, hydrogeological and hydrochemical data were compiled through numerical and geostatistical calculations and then integrated into a GIS environment. The two sensitivity maps are derived from the integration of two methods: the irrigation water sensitivity map and the drinking water supply sensitivity map.

The pollution results of these two water sensitivity maps (two years considered in 2010 and 2018) are compared with different chemical water quality maps of the Mitidja alluvial aquifer. Our conclusion is that the index method adopted by Algeria for the second time in the same groundwater is reliable. It confirms the pollution of the water by nitrates and chlorides, and therefore provides time for the water and environmental policy makers to take action against this phenomenon.

In this regard, all measures should be taken to protect the water resources, which are constantly under threat, and the conditions for the water resources administration to establish near-shore and far-shore protected areas should be reviewed. In addition, regulations and standards for the use of phytosanitary products in agriculture should be reviewed.

Acknowledgments

The Authors would thank the Prof. Riccardo Salvini of CGT Centre for GeoTechnologies of University of Siena (Italy), for their support, attention and useful discussions. The Authors would like to thank the anonymous reviewers for their helpful comments and suggestions.

References

Aller I., Benett T. 1987. DRASTIC a standardized system for evaluation of ground water pollution. Potential using hydrogeology setting. Rapport EPA, NWWA. Ohio, USA, 455, 22 carts.

Ayme A. 1956. Contribution à l'étude de la plaine de la Mitidja occidentale et de sa bordure.

Aziez O. 2021. Efficacité économique et environnementale des instruments de gestion de l'eau, pour des eaux souterraines utilisées en irrigation dans la Mitidja ouest. Thèse de doctorat Es-science. Université Aboubakr Belkaïd. Tlemcen. Faculté de Technologie, 220 p.

Bennie et Partners. 1983. Schéma d'aménagement des ressources en eau dans la région d'Alger.

Benouara N., Bouchehed H., Retima N. et al. 2024. Evaluation of Groundwater Quality for Irrigation Purposes Using Water Quality Indices and GIS Technique: A Case Study of Seriana Plain Northeastern Algeria. Dokl. Earth Sc., 515, 477–489. https://doi.org/10.1134/S1028334X23602596

Benziada M. 1994. Etude hydrogéologique de la plaine de la Mitidja Est. Application d'un modèle mathématique 'ASM' au bassin côtier algérois. Thèse de Doctorat. Université de Franche-Comté en Sciences de la Terre.

Bouderbala A. 2019. The impact of climate change on groundwater resources in coastal aquifers: Case of the alluvial aquifer of Mitidja in Algeria. Environmental Earth Sciences, 78, 698. https://doi.org/10.1007/s12665-019-8702-5

Copernicus. 2023. Surface air temperature for July 2023. Implemented by ECMWF as part of The Copernicus Programme. https://climate.copernicus.eu/surface-air-temperature-july-2023

Djabri L., Hani A., Mania J., Mudry J. 2003. L'Algérie, un pays en développement. A-t-elle déjà développé un biseau salé? Technologia de l'intrusion de agua de mar en acuiferos costeros. Madrid.

Djoudar Hallal D. 1993. Approche du comportement hydrodynamique d'un système aquifère alluvial. Zone Oued El Harrach/Oued El Hamiz (Mitidja/Algérie). Mémoire d'ingénieur. IST/USTHB Alger.

Djoudar Hallal D., Toubal A.C. 2012a. Contribution à l'étude de la pollution des eaux souterraines : Cas de la nappe du Haut Chellif . Bulletin du Service Géologique National de l'Algérie (SGA). ANGCM. Vol. 23. N°1.pp 71-83. 2012.

Djoudar Hallal D., Toubal A.C. 2012b. Indexation de la sensibilité combinée à l'évaluation du risque de dégradation de la qualité des eaux souterraines à la pollution. Cas de la nappe alluviale de la Mitidja. IAHS – Medfriend Conference, 14–16 November, Istanbul.

Djoudar Hallal D., Toubal A.C. 2014. Geostatistical modeling of nitrate pollution of groundwater in the Mitidja. 6th IAHS International Symposium on Integrated Water Resources Management 4-6 June Bologna. Italie.

Djoudar D. 2014. Methodological approach of the vulnerability of the underground water resource in a strongly urban area: example in Algeria of the coastal plains (Mitidja). Doctorate Es-Sciences thesis, FSTGAT, USTHB, Alger.

Djoudar D. et al. 2019. Application of the GALDIT method combined with geostatistics at the Bouteldja aquifer (Algeria). Environ. Earth Sci., 78, 22.

Drouiche A. 2012. Contribution à l'étude de la vulnérabilité spécifique à la pollution par les éléments en traces métalliques et les hydrocarbures. Cas de la nappe d'eau souterraine de la Mitidja-Est. Université des sciences et de la technologie Houari Boumediène (USTHB). Magistère.

Durand Delga M. 1969. Mise au point sur la structure du NE de la Berbérie. Publ. Serv. Carte géologique. Algérie, 39, 85–131.

Geovariances. 2007. Isatis 7.0., case studies, p. 507.

Glangeaud A. 1952. Etude géologique de la région littorale d'Alger. Bull. Serv. Carte. Géol. Algérie, 2 , 8.

Gouaidia et al. 2012. Évaluation de la salinité des eaux souterraines utilisées en irrigation et risques de dégradation des sols: exemple de la plaine de Meskiana (Nord-Est Algérien) Physio-Géo, 6, 1, 141–160.

Guastaldi E., Del Frate A. 2012. Risk analysis for remediation of contaminated sites: The geostatistical approach. Environmental Earth Sciences, 65(3), 897–916. http://dx.doi.org/10.1007/s12665-011-1133-6.

Guastaldi E., Graziano L., Liali G. et al. 2014. Intrinsic vulnerability assessment of Saturnia thermal aquifer by means of three parametric methods: SINTACS, GODS and COP. Environ. Earth Sci., 72, 2861–2878. https://doi.org/10.1007/s12665-014-3191-z.

Guendouz A., Moula A. 2017. Assessment of seawater intrusion in the bay of Algiers (Algeria) by means of a combined isotope hydrology and hydrogeochemistry approach. October 2017 Conference: Eau – Société – Climat (ESC-2017), Hammamet, Tunisia.

Hadjoudj O. 2008. Pollution des nappes aquifères de la Mitidja par les nitrates. Thèse de doctorat de l'Université d'Alger, Benyoucef Benkhedda, p. 290.

Haouchine A. et al. 2016. Assessment of risk related to Coastal Aquifers Management in Algeria. La Houille Blanche, 102, 6, 36–43. https://doi.org/10.1051/lhb/2016058

Ikhlef N., Tachi S.E., Bouguerra H. et al. 2024. Classification of Groundwater Quality for Irrigation Purposes in Wetland Region by Irrigation Water Quality Index. Water Resources, 51, 322–331. https://doi.org/10.1134/S0097807823600493.

Khous D., Aitamar H., Belaid M., Chorfi H. 2019. Geochemical and isotopic assessment of groundwater quality in the alluvial aquifer of the Eastern Mitidja Plain. Water Resources, 46(3), 443–453. https://doi.org/10.1134/S0097807819030060

Mania J., Imersoukene S., Braillon J.M. 1985. Pollution saline de la nappe côtière à l'est d'Alger. Revue Hydrogéologie, 3, 213–226.

Margat J. 1968. Vulnerabilite des nappes d'eau souterraine a la pollution (Groundwater Vulnerability to Contamination). Bases de la cartographie (Doc.) 68 SGC 198HYD, BRGM, Orleans.

Medjdoub Leulmi S., Aidaoui A., Djoudar Hallal D., Khelfi M.A., Lobo Ferraira J.P., Ammari A., Aziez O. 2021. Spatio-temporal analysis of nitrates and piezometric levels in groundwater using geostatistical approach: Case study of the Eastern Mitidja Plain, North of Algeria. 27 February. Arabian Journal of Geosciences, 14, 386. doi.org/10.1007/s12517-021-06642-1.

NWRA. 2018. National Water Resources Agency. General Directorate of Algiers, Algeria.

Ouchene B., Moroncini O. 2018. De l'économie socialiste à l'économie de marché: l'Algérie face à ses problèmes écologiques. https://doi.org/10.4000/vertigo.22166

PAC. 2004. Maitrise de l'urbanisation et de l'artificialisation des sols. Projet d'aménagement. Rapport: Etude prospective de l'urbanisation Phase 2. 66 pages.

Pusatli T.O., Camur Z.M., Yazicigil H. 2007. Susceptibility indexing method for irrigation water management planning: Applications to K. Menderes river basin. Turkey. Department of Geological Engineering. Middle East Technical University. Ankara. Turkey. Journal of Environmental Management, 90, 1, 341–347.

Saidi S., Bouri S., Bendhia H., Anselem B. 2009. A GIS based susceptibility indexing method for irrigation and drinking water management planning: Application to Chebba – Mellouli ch aquifer. Tunisia.

Tachi S.E., Bouguerra H., Djellal M. et al. 2023. Assessing the Risk of Groundwater Pollution in Northern Algeria through the Evaluation of Influencing Parameters and Ensemble Methods. Dokl. Earth Sci., 513, 1233–1243. https://doi.org/10.1134/S1028334X23600767.

WHO. 2011. World Health Organization. Guidelines for drinking-water quality, 4th ed.