



A GIS-based approach for geospatial modeling of groundwater vulnerability and pollution risk mapping in Bou-Areg and Gareb aquifers, northeastern Morocco

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Abstract

Groundwater resources are the main supply of freshwater for human activities. Nevertheless, during the last 50 years, groundwater has become very susceptible to chemical pollution due to human activities. The groundwater vulnerability assessment constitutes a worldwide recognized tool for water management and protection. In this study, the GIS-based DRASTIC and pollution risk models have been used to assess the intrinsic vulnerability and risk to pollution of the Gareb and Bou-Areg aquifers, the main irrigated areas in the northeast of Morocco, by analyzing available hydrogeological attributes. The seven hydrogeologic factors used to assess vulnerability were depth to aquifer, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity, while an eighth parameter has been added to assess the pollution risk which is the land use. The resultant vulnerability map reveals that about 0.06% of the study area is in low vulnerability zones, 83.68% is moderately vulnerable, and 16.26% is highly vulnerable to groundwater pollution. The results also reveal that groundwater is highly vulnerable in the Gareb aquifer and the coastal zone, where the water table is very low, the slope is gentle, and the geological formations are permeable. In addition, moderate to low vulnerability is found towards the west of the study area where the groundwater is located in deep aquifers. The groundwater pollution risk map is obtained by overlaying the land use with the DRASTIC vulnerability. The central and western parts of Bou-Areg as well as the south of Gareb are dominated by high and very high pollution risk classes, and present 43.07% of the study area, which is strongly influenced by urban areas, agricultural activities, and shallow groundwater systems. 30.11% of the surface is moderately vulnerable, mainly in areas where human activity is not widely observed, while the very low and low pollution risk classes represent a total of 26.82% of the total area. The mapping models were validated using nitrate concentration and electrical conductivity data in groundwater as an indicator of pollution. A positive correlation was observed when validating these models. The resultant groundwater vulnerability

and pollution risk maps might provide an early warning to policy maker and manager to manage and avoid further stress on this invaluable resource.

Keywords Groundwater vulnerability · Pollution risk · DRASTIC model · Land use · Nitrate contamination · GIS

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Introduction

Groundwater constitutes a life-sustaining and essential resource throughout the world (Busico et al., 2020, b). It is the most significant source of potable water in many countries because of their relatively low vulnerability to pollution compared to surface water, its availability, easy accessibility, and less costly (Jahromi et al. 2020). Aquifers are highly susceptible to the impact of unregulated exploitation and inadequate

land use, causing risk to the quality of groundwater (Bouchaou et al. 2009). Decreased groundwater quality is commonly linked to the uncontrolled and increased use of chemical compounds, whereas the population growth and climate change worsen this situation (Ersoy and Gültekin, 2013; Razandi et al. 2015; Chafouq et al. 2018; Barzegar et al. 2019). As the use of polluted water can be hazardous to human health, prevention and early warning have become necessary to ensure water quality (Busico et al., 2020, b). Vulnerability mapping is a very important tool for groundwater management (Herlinger and Viero 2007).

The notion of groundwater vulnerability was first introduced in France by Margat (1968), wherein groundwater vulnerability was defined as the ability of infiltration and diffusion of contaminants from the soil surface in the groundwater system. Groundwater vulnerability can be described as an intrinsic characteristic of a groundwater system that depends on the sensitivity of that system to natural and human impacts (Vrba and Zaporozec, 1994). However, in addition to an intrinsic vulnerability that focuses purely on hydrological factors, there is also a specific vulnerability that includes factors related to anthropogenic activities such as the type of pollutant and land use (Ribeiro et al. 2017).

Researchers developed more than 30 methods to determine the vulnerability of groundwater. Three main approaches are available for aquifer vulnerability assessment: index-overlay, statistical, and process-based (National Research Council 1993; Wu et al. 2016). The choice of the more appropriate method to assess vulnerability is highly dependent on the objective and scope of a particular study, data availability, and especially, the user's cost and time (Liggett and Talwar 2009; Hasan et al., 2019a, b). The index-overlay models are less restricted by computational difficulties and data shortages (Barbash and Resek 1996; Shrestha et al. 2017). Over the years, numerous overlay methods such as DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stempvoort et al. 1993), and SINTACS (Civita 1994) have been used, among many others, for vulnerability studies (Dörfliger et al. 1999; Liu et al. 2003; Shirazi et al. 2013; Narany et al. 2014; Kura et al. 2014; Noori et al. 2019).

The assessment of groundwater contamination is a growing concern in the scientific community. As spatial data become increasingly available and the use of GIS, groundwater vulnerability mapping has become a widely used tool for groundwater resource management and protection (Jha et al. 2007). Among all available GIS-based mapping techniques, DRASTIC—a combination of depth to aquifer (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C)—is the most popular (Hasan et al., 2019a, b). The DRASTIC methodology is based on four main assumptions: the contaminant is introduced at the soil surface, the contaminant is transported to the groundwater by precipitation, the

contaminant has the mobility of water, and the area assessed is 0.4 km² or more (Aller et al. 1987; Herlinger and Viero 2007). The vulnerability extent in this method is determined by considering the indices of weights, ranges, index, and classification (Shrestha et al. 2016; Jaunat et al. 2019).

Recently, a modification of the DRASTIC model has been carried out by integrating it with the multi-criteria analysis-analytical hierarchical process (MCA-AHP) model (Neshat et al. 2014; Saida et al. 2017; Jesiya and Gopinath 2019), the artificial neural network (ANN) (Baghapour et al. 2016), and anthropogenic influence (Singh et al. 2015; Jaunat et al. 2019). However, the majority of studies did not adequately account for the human factor in their analysis as the other DRASTIC parameters. The influence of land use (LU) on groundwater contamination also has been identified as a parameter that receives less attention and focus by most researchers (Asfaw and Ayalew 2020). Various studies (Saha and Alam 2014; Al-Abadi et al. 2017; Bhuvaneshwaran and Ganesh 2019) for example did not include the impact of LU on aquifer vulnerability and its contribution to the contamination of groundwater. However, it is essential to consider the impact of LU in the examination of aquifer vulnerability since a change in land cover has an impact on the vulnerability of groundwater to pollution (Asfaw and Ayalew 2020).

The Mediterranean basin is considered among the most arid areas in the world, where limited water resources are spatially and temporally unevenly distributed (Re et al. 2014). In Morocco, irrigated agriculture has become the largest consumer of groundwater (Bouras et al. 2019), a crucial sector of the Moroccan economy, representing approximately 15% of GDP and employing around 43% of the workforce (Brouziyne et al. 2018), raising questions about sustainability and irreversible degradation of the resource, ultimately resulting in numerous cross-sectoral policy and management issues. The region of Nador in northeastern Morocco, like many other coastal plains along the Mediterranean, is characterized by extensive agricultural activities corresponding to more than 62% of the total area (El Yaouti et al., 2008), especially in the Bou-Areg and the Gareb plains with 10180 ha and 13500 ha respectively, exploited both for local consumption and for agro-industrial production (Khattabi and El Ghazi 2008). Recently, this region saw the launch and the implementation of many structuring socio-economic projects. Certainly, the fulfillment and the achievement of anticipated projects will need access to water in sufficient quantity and quality.

Groundwater research in Morocco has been mainly focused on hydrogeological and hydrogeochemical aspects, such as groundwater potential, groundwater quality, and hydrogeological modeling (Rochdane et al. 2015; Ait Brahim et al. 2015; Sefiani et al. 2019; Bouimouass et al. 2020; Hssaisoune et al. 2020). However, very little has been attempted in the context of vulnerability due to natural and human impacts (urbanization and industrialization) such as

(Sinan and Razack 2009; Jilali et al. 2015; Heiß et al. 2020). According to El Yaouti et al. (2009) and Re et al. (2014), the groundwater quality in the region of Nador has been deteriorated in recent years mainly because of agricultural activities and urban inputs. This requires a vulnerability study and risk to pollution mapping of this area with the aim of providing contemporary information on groundwater pollution and identify areas at risk to protect its quality and ensure its sustainability.

Materials and methods

Site description

The study area is composed of two horizontally connected aquifers located in the northeast of Morocco, Bou-Areg and Gareb aquifers. The study region covers an area of 522 km², corresponding to the extension zone between the latitudes 34° 91' N and 35° 17' N and the longitudes 2° 66' E and 3° 15' E and which is limited by the Gareb-Kebdana mountain range to the south and east and by the Tiztoutine and Beni Bou Ifrou mountains to the west (Fig. 1a). The area is open to the

Mediterranean Sea in the north (Bou-Areg lagoon, locally known as Sebkhia Bou-Areg or Marchica) (Chamrar et al. 2019). These two plains are agricultural and considered as the main irrigated areas in the northeast of Morocco. According to El Yaouti et al. (2008) and Chamrar et al. (2019), the climate of the region is semi-arid to humid and typically Mediterranean, with low and irregular annual rainfall. The annual temperature in the study area ranges from a maximum of 34.5 °C to a minimum of 11.5 °C.

Bou-Areg plain

Bou-Areg coastal plain (Fig. 1a) is limited to the north by the arched shape of the Bou-Areg lagoon, to the east by the chains of Kebdana, to the northwest and west by the Gourougou massifs and Ibn-Bou-Ifrou (El Yaouti et al. 2009). The main aquifer is unconfined and consists of two Plio-Quaternary formations (Fig. 1b), the upper one of fine silts, and the lower of coarse silts with sand and gravel. The aquifer is supported by a marly bedrock of Miocene age that plunges towards the coastal lagoon of Bou-Areg. The bedrock of the water table consists of a marly rock of Miocene age that plunges towards the coastal lagoon of Nador (El Mandour et al. 2006).

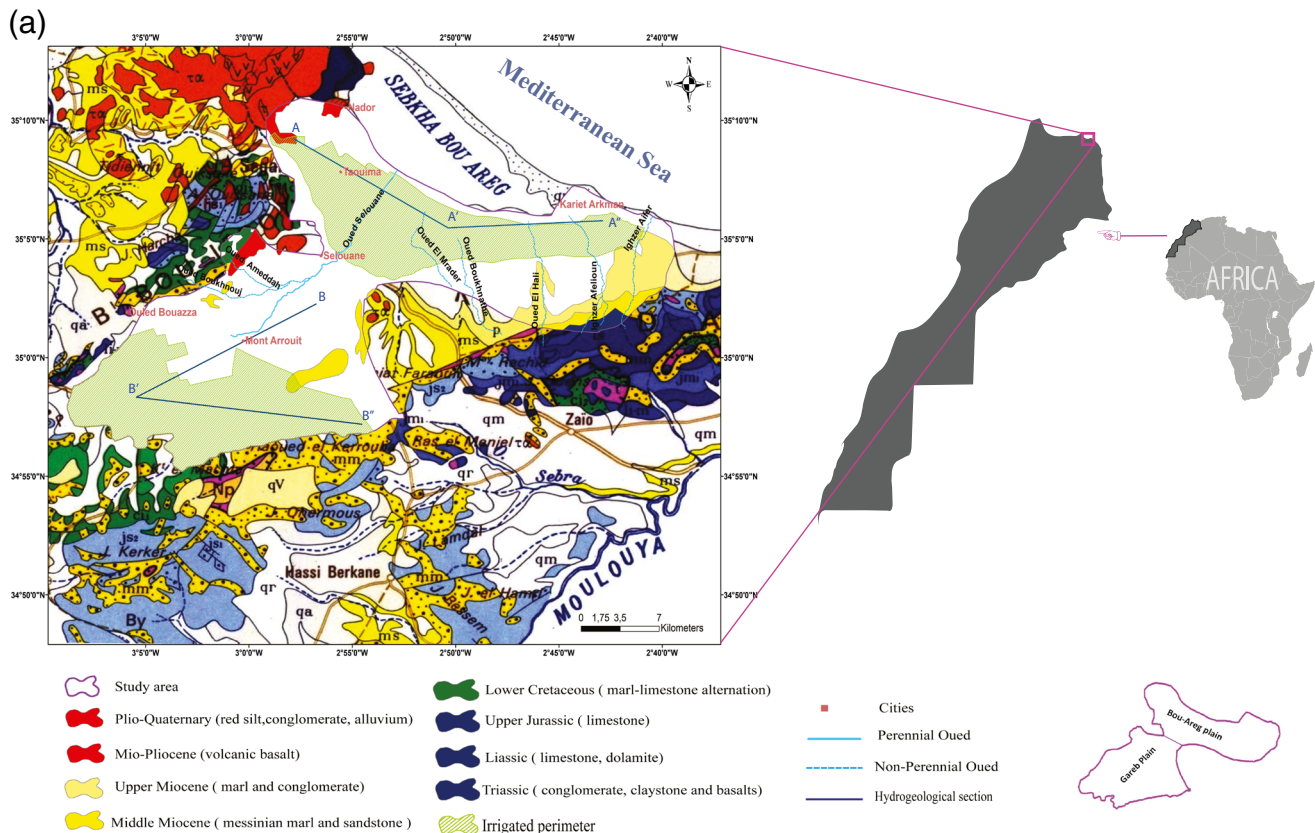


Fig. 1 Location map of Bou-Areg and Gareb aquifers (a). Cross-sectional view of subsurface geology and hydrogeological system of the Bou-Areg aquifer (b) and Gareb aquifer (c)

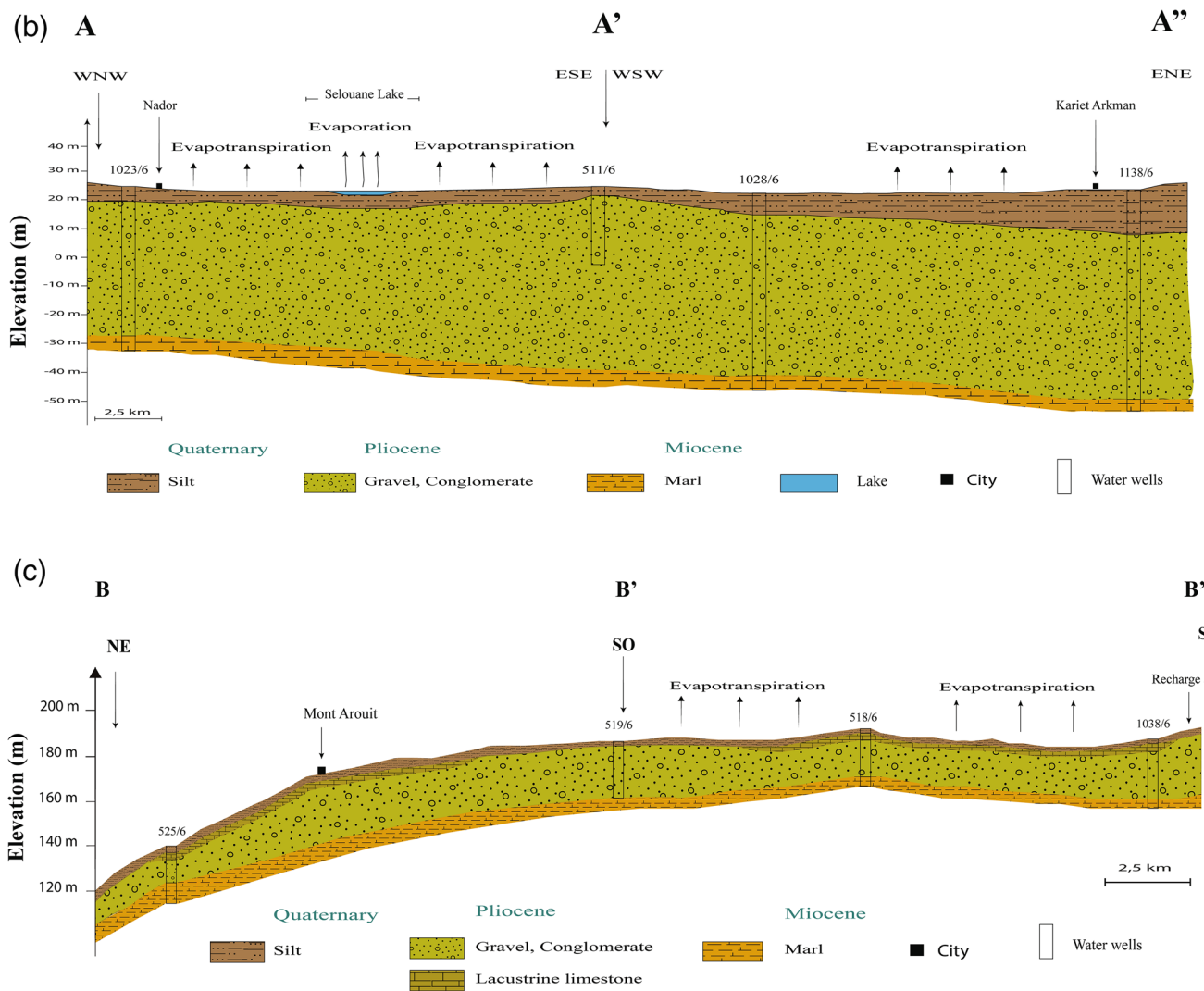


Fig. 1 continued.

Gareb plain

Gareb plain is located south-southwest of Nador, elongated in a west-eastern direction separated from the Bou-Areg plain by the plio-villafranchian plateaux of Selouane. The aquifer is mainly composed of Villafranchian marly limestone (Fig. 1c). The southwestern part of the plain contains silt gravel, while the eastern part is composed of conglomerates. Like Bou-Areg, the impermeable basement is yellowish marls of Miocene (Lyazidi et al. 2020).

Vulnerability assessment using DRASTIC model

The groundwater vulnerability was assessed using hydrogeological parameters that can affect the transport of pollutants through the vadose zone to the aquifers using the GIS-based DRASTIC model (Arya et al. 2020). The DRASTIC method was developed for the

U.S. Environmental Protection Agency (EPA) by Aller et al. (1987); it is composed of two main parts: the identification of mappable units, and the implementation of a numerical scheme of relative ranking of hydrogeological features (Herlinger and Viero 2007). The DRASTIC model employs seven hydrogeological factors, namely the depth to aquifer (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C); every parameter is noted in a range from 1 to 10 based on a range of values. Lower score signifies a less contribution to the global vulnerability of groundwater and vice versa (Kura et al., 2014; Shrestha et al., 2017). The ratings are then multiplied by a relative weight based on its relative importance (Babiker et al. 2005; Nadiri et al. 2019). The weights range from five (most important) to one (least significant), as shown in Table 2. The final groundwater vulnerability map was created following the methodology

Table 1 Data used for creation of hydrogeological parameters for DRASTIC and pollution risk models

Parameter N°	Raw data	Source	Output layer
1	Groundwater levels	Field survey (April 2018)	Depth to aquifer (D)
2	Recharge data	ORMVAM	Net recharge (R)
3	Well log data	ABHM	Aquifer media (A)
4	Soil data	ABHM	Soil media (S)
5	Digital elevation model (DEM)	ASTER (https://asterweb.jpl.nasa.gov/gdem.asp)	Topography (T)
6	Well log data	ABHM	Impact of vadose zone (I)
7	Well pumping, test data	ABHM	Hydraulic conductivity (C)
8	Satellite imagery	Copernicus Global Land Operations (https://africa.lcviewer.vito.be/2018)	Land use (LU)

shown in Fig. 2. It is an expression in the form:

$$\begin{aligned} \text{DRASTIC index (Di)} = & D_r D_w + R_r R_w + A_r A_w \\ & + S_r S_w + T_r T_w + I_r I_w \\ & + C_r C_w \end{aligned} \quad (1)$$

where subscript r is rating and w is weight.

Data source

The application of the DRASTIC method is based on seven parameters to be the most crucial in the contamination process (Aller et al. 1987): depth to aquifer, net recharge, aquifer media, soil media, topography (slope), impact of the vadose zone, and hydraulic

conductivity. The raw data were collected or derived from various sources and are listed in Table 1. All thematic layers for different hydrogeological parameters were generated using ArcGIS Software. The full data modeling process is illustrated in Fig. 2.

ORMVAM, Office Régional de Mise en Valeur Agricole de la Moulouya; ABHM, Agence du bassin hydraulique de la Moulouya

Preparation of DRASTIC parameter maps

Depth to aquifer

The depth to aquifer is defined as the perpendicular distance between the upper edge of the surface and the upper edge of

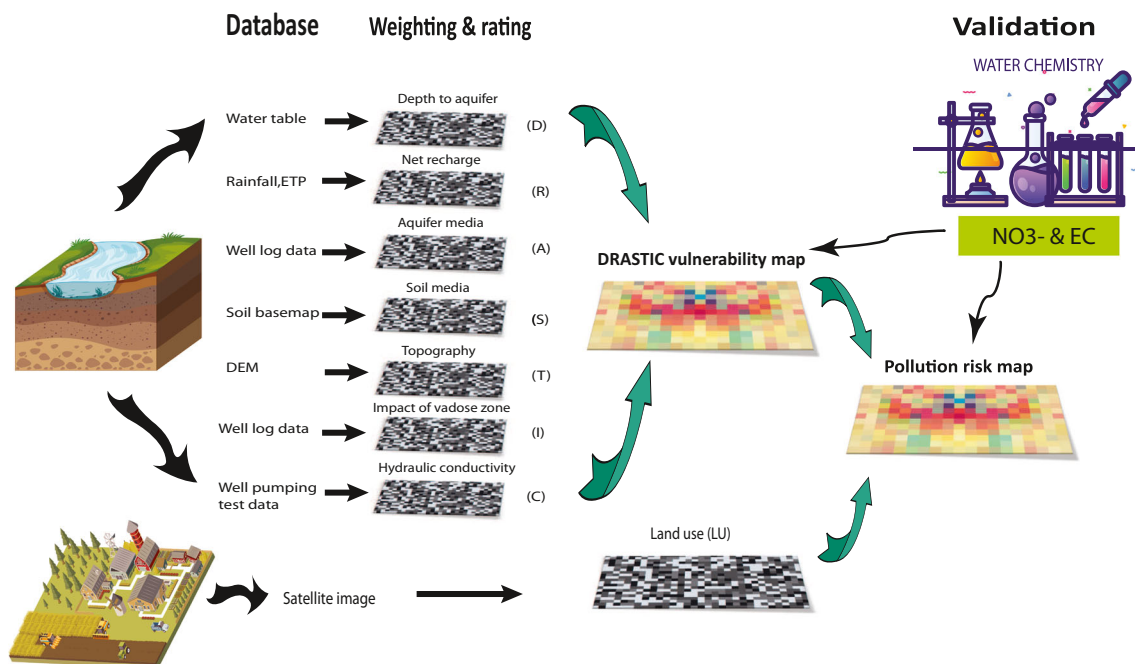


Fig. 2 Flowchart of the DRASTIC and pollution risk models

the groundwater surface (Khosravi et al. 2018). The depth to aquifer map has been realized from measurements collected during a campaign organized by our team in April 2018. Water level data of 50 domestic and agricultural wells (Fig. 3) were used to interpolate depth to aquifer by inverse distance weighted (IDW) method provided in the spatial analyst tool of ArcGIS10. The depth to aquifer varied from 2.4 to 160 m and was classified into six depth categories: 1.5–4.6 m, 4.6–9.1 m, 9.1–15.2 m, 15.2–22.8 m, 22.8–30.4 m, and > 30.4 m. Based on the DRASTIC approach, higher depths present less contamination potential and vice versa; hence, the subclasses of the parameter D were classified accordingly. The highest score of 9 was assigned to the shallowest depth range in the study area which varied from 1.5 to 4.6 m, followed by 7 for 4.6–9.1 m, 5 for 9.1–15.2 m, 3 for 15.2–22.8 m, 2 for 22.8–30.4 m, and 1 for > 30.4 m (Table 2).

Net recharge

Recharge is the amount of water that penetrates the soil and reaches the water table (Neshat et al. 2014). It expresses the means of contaminant transport to the aquifer. These amounts can be the result of irrigation returns, rainfall, or recharge from rivers and lakes. The recharge values for the study area were obtained from ORMVAM (Office Régional de Mise en Valeur Agricole de la Moulouya). Based on the provided data, groundwater recharge values exhibit a variation from 137 to 200 mm/year in the study area. Recharge values were classified into two categories: 101.6–177.8 mm/year and 177.8–254 mm/year. The aquifer of Bou-Areg was classified in the 101.6–177.8 range because of its values ranging from 137 to 155.04 mm/year, while the Gareb aquifer was classified in two ranges: 101.6–177.8 mm/year and 177.8–254 mm/year since it includes values ranging from 113.04 to 200 mm/year. Areas with higher recharge were

given relatively high ranking values. A rating of 8 was assigned to the 177.8–254 mm/year class and 6 to 101.6–177.8 mm/year (Table 2).

Aquifer media

The aquifer is a layer of permeable rock, which has storage capacity. A permeable aquifer with a high degree of recharge can lead to high vulnerability and vice versa (Yang et al. 2017). The map representing aquifer media was produced from boreholes profile of the study area (Fig. 3) developed by the ABHM (Agence du bassin hydraulique de la Moulouya). Four distinct lithologies define the aquifers in the study area, namely clay loam and gravel, conglomerate, the limestone lacustrine, and silt and gravel. The attenuation of contaminants in the aquifer is related to grain size and sorting. The permeability is increased with larger grain size, which reduces the attenuation potential and consequently increases the pollution potential (Anwar et al. 2002; Hasan et al., 2019a, b). A score of 10 is assigned to lacustrine limestone, 8 for conglomerates and 5 for both silt and gravel and clay loam and gravel.

Soil media

Soil media refers to the uppermost portion of the vadose zone characterized by significant biological activity (Jaunat et al. 2019). It is considered the layer that controls the quantity of water able to penetrate it to reach the water table (Ouedraogo et al. 2016). The soil map was obtained by digitizing existing soil texture map carried out by ORSTOM-France (Office de la Recherche Scientifique et Technique Outre-Mer), now called IRD (Institut de recherche pour le développement), in 1963. Three soil textures were identified in the study area, clay loam, limestone silt, and alluvium. According to Aller et al. (1987), the presence of fine-textured materials such as silts and clays

Table 2 Ranges, ratings, and weight of DRASTIC parameters (Aller et al. 1987; Asfaw and Ayalew 2020)

Depth to aquifer (D)		Net recharge (R)		Aquifer media (A)		Soil media (S)		Topography (T)		Impact of vadose zone (I)		Hydraulic conductivity (C)	
Range	Rating	Range	Rating	Range	Rating	Range	Rating	Range	Rating	Range	Rating	Range	Rating
> 30.4	1	101.6–177.8	6	Clay loam and gravel	5	Clay loam	3	< 18	1	Clay loam and clay	3	12.3–28.7	4
22.8–30.4	2	177.8–254	8	Silt and gravel	5	Limestone silt	6	12.0–18	3	Silt and gravel	4	28.7–41	6
15.2–22.8	3			Conglomerate	8	Alluvium	10	6.0–12	5	Conglomerate	6	41–82	8
9.1–15.2	5			Karsts limestone	10			2.0–6	9				
4.6–9.1	7							0–2	10				
1.5–4.6	9												
Weight: 5		Weight: 4		Weight: 3		Weight: 2		Weight: 1		Weight: 5		Weight: 3	

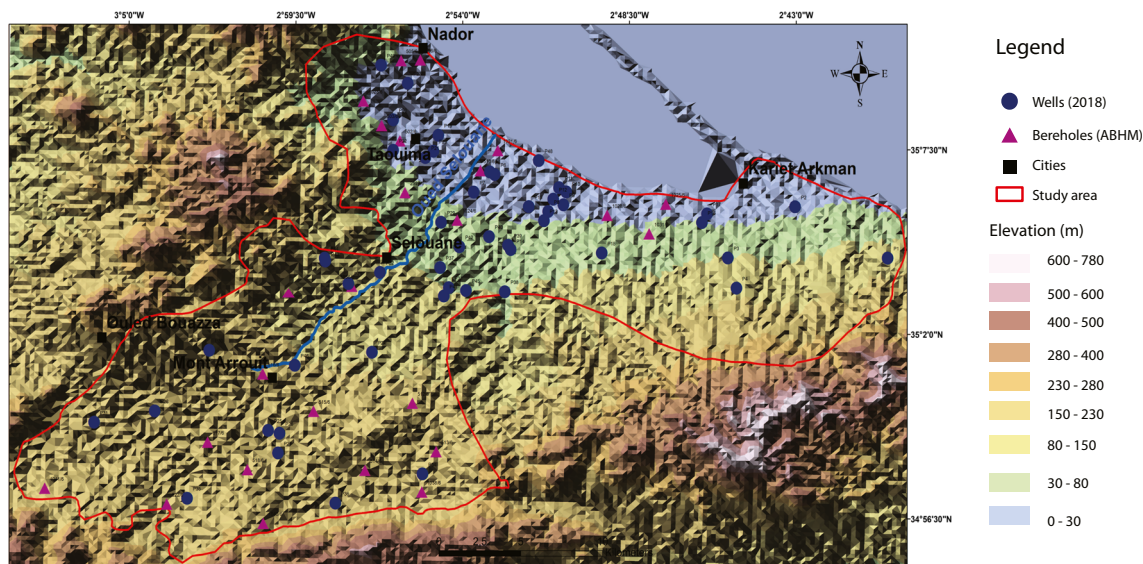


Fig. 3 Location of sampling wells and ABHM boreholes in the study area

may decrease relative to soil permeability and limit contaminant migration. Alluvium was given a high rating of 10 because of its high permeability; it is the least able for preventing the migration of pollutants to the aquifer, while clay loam was given a low rating of 3 (Table 2).

Topography

The topography represents the slope of the study area. It controls the likelihood of a contaminant to be transported by runoff or to be retained on the ground where it may percolate (Aller et al. 1987). The gentler the slope, the higher is the retention capacity of water and/or pollutants, whereas the steeper the slope ($> 18\%$), the lower is the retention capacity of water and/or pollutants. The topographic map was obtained from the digital elevation model (DEM) and converted into a slope using a 3D Analyst tool, based on the spatial analyst tool in ArcGIS10. The area has flat landscape; therefore, slope percentage variation was found to be very small varying from 0 to 18° in the whole study area, and reaching 30° in a narrow zone towards the western massifs. Besides, the slope values were reclassified by giving each class of values its rating, which is between 1 and 10. The entire slope map was classified into five classes as 0–2%, 2–6%, 6–12%, 12–18%, and $> 18\%$. Very flat terrain with 0–2 % slope was given the highest rank of 10, whereas water can last longer in flat areas, allowing pollutants to percolate easily into the aquifer (Hasan et al., 2019a, b). Two to 6%, 6–12%, 12–18%, and $> 18\%$ slopes were rated 9, 5, 3, and 1 respectively.

Impact of vadose zone

The vadose zone, also called the unsaturated zone, is a layer of sediment located above the water table and below the soil. This

zone controls the duration of the water passage to the aquifer while controlling contaminant input (Yang et al. 2017). It is important for pollutant attenuation because many physical and chemical reactions occur in this area, such as neutralization, mechanical filtration, biodegradation, dispersion, and volatilization (Aller et al. 1987; Wu et al. 2016). The map of the vadose zone was performed from lithological logs (Fig. 3) using similar techniques that were adopted for the aquifer media. Vadose zone materials were found to be dominantly silt and gravel, conglomerate and limestone, clay loam, and finally clay. Each geological unit was given assigned rating factors (Table 2).

Hydraulic conductivity

The hydraulic conductivity, noted K, determines the flow rate of contaminants in the groundwater system. Aquifers having a higher conductivity are more susceptible to contamination, as they transmit pollutants for easy movement (Arya et al. 2020). High conductivity values will be associated with high potential for contamination (Rahman 2008). The hydraulic conductivity map was created using the results of aquifer tests performed by ABHM on the boreholes (Fig. 3). The hydraulic conductivity ranged from 14 to 60 m/day. The entire study area was divided into three subclasses of 12.3–28.7 m/day, 28.7–41 m/day, and 41–82 m/day. A faster contamination is generally observed in an aquifer if it contains higher hydraulic conductivity and vice versa. A moderate to high ranking was assigned to the subclasses with 4 for 12.3–28.7 m/day and 6 for 28.7–41 and 8 for 41–82 m/day (Table 2).

Intrinsic vulnerability mapping

The DRASTIC index (Di) was calculated by multiplying each parameter by its respective weight (Table 2) and adding the

seven map parameters according to Eq. (1). This operation is executed using the function Raster Calculator of Spatial Analyst tool in ArcGIS10. Then, the resulting map is reclassified according to vulnerability classes (Engel et al. 1996), in order to give each class its degree of vulnerability. Di values were then reclassified to represent low to high vulnerability ranks. A low vulnerability class is assigned for values less than 100, a medium vulnerability class is assigned for values between 101 and 140, a high vulnerability class is assigned for values between 141 and 200, and for above 200, the vulnerability is considered very high (Engel et al. 1996; Ersoy and Gültekin 2013).

Pollution risk map

The pollution risk of groundwater corresponds to the ability of a groundwater body for undergoing groundwater pollution (Farjad et al. 2012). Pollution risk is determined simultaneously by the intrinsic vulnerability of the aquifer, which is relatively static, and by the presence of potentially contaminating activities at the soil surface (Ouedraogo et al. 2016). Land cover change from natural vegetation into farming, industrial activity, and settlement produces waste and chemical pollutants that contribute to the contamination of poorly maintained springs and boreholes (Eldrandaly et al. 2005).

Since vulnerability mapping considers only the hazards threatening groundwater and ends up with the potential impact of pollutants, and in order to include the impact of actual contamination and considering the origin and nature of the pollutant, an additional LU parameter is used in the analysis (Garewal et al. 2017). DRASTIC model was modified to take into account the change in land cover and expressed as a specific vulnerability model, called pollution risk.

Land use refers to the modification of land cover due to human processes (Kennedy et al. 2009). According to Andreo et al. (2006) and Busico et al. (2017), the evaluation of the risk intensity logically includes all the activities that consider all possible sources of contamination. The pollution risk map promotes the understanding of the impact of natural and anthropogenic activities on the surface of the soil, therefore allowing the identification of sources of pollution (Singha et al. 2019).

Many human activities and LU forms have significant impacts on the groundwater vulnerability throughout most of the area, especially the Gareb and Bou-Areg plains as they are among the most agricultural productive regions in northeastern Morocco. According to El Yaouti et al. (2009) and Re et al. (2014), groundwater quality in study area is being deteriorated because of many anthropogenic activities.

The land use map of Africa was downloaded from (<https://africa.lcvviewer.vito.be/2018>) and clipped along the boundary of the study area and subsequently reclassified using ArcGIS10 according to the classes in Table 3, from which

we obtained the land use map of the study area (Figs. 4 and 5). The land use map of the study area is distributed into five classes; each category has a score. A rating of 10 for cultivated land, 8 for urban area, 4 for grazing land, 2 for water body, and the last score of 1 for forest and plantation tree (Rupert 2001; Asfaw and Ayalew 2020). The land use map must be reclassified according to the scores assigned to each category, and then multiplied by its assigned weight, which is equal to 5. A weighting value of 5 was assigned to the land use factor (Secunda et al. 1998; Panagopoulos et al. 2006), recognizing the important role of contaminant load on the determination of nitrate concentrations in groundwater (Mfumu Kihumba et al. 2017). The resultant grid coverage was then added to drastic parameters to obtain the pollution risk map following Eq. (2): (Al-Adamat et al., 2003; Ouedraogo et al., 2016)

$$\text{Risk map index} = Di + (LUr * LUw) \tag{2}$$

Where

DI = DRASTIC index

LUr and LUw are ratings and weights for each parameter.

Model validation

Validation of a model is mandatory for the eventual use of its results (Hasan et al., 2019a, b). Ravbar and Goldscheider (2009) state that there is no common and standard practice for validating vulnerability maps and several researchers have used various models to validate vulnerability map results (Barbulescu 2020). Consequently, alternative techniques should be used, such as the validation of vulnerability maps based on contaminant datasets obtained on-site from wells throughout the study area (Gogu and Dassargues 2000). El Yaouti et al. (2009) and Re et al. (2013) found through their hydrogeochemical study that the water quality of the Bou-Areg plain is extremely degraded, while no hydrogeochemical data are available for the Gareb plain. For this purpose, geochemical measurements were carried out in the field to sample groundwater assess the local nitrate footprint and electrical conductivity. A total of 50 groundwater samples were collected from domestic and agricultural wells in April 2018

Table 3 Main soil occupation classes and their corresponding land use values (Rupert 2001; Asfaw and Ayalew 2020)

Land classification according to the corine land cover	Land use rating
Forest and plantation tree	1
Water body	2
Grazing land	4
Urban area	8
Cultivated land	10

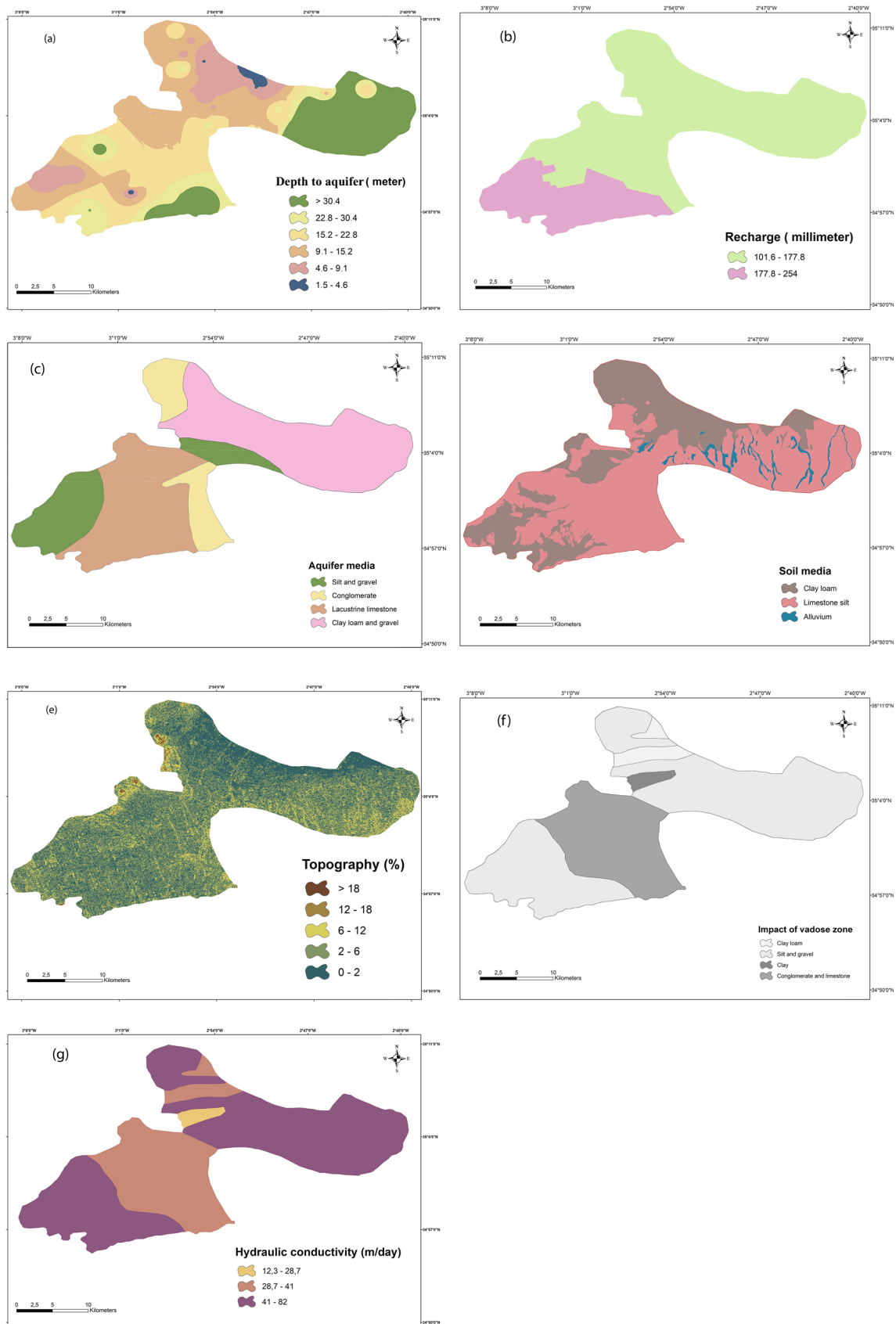
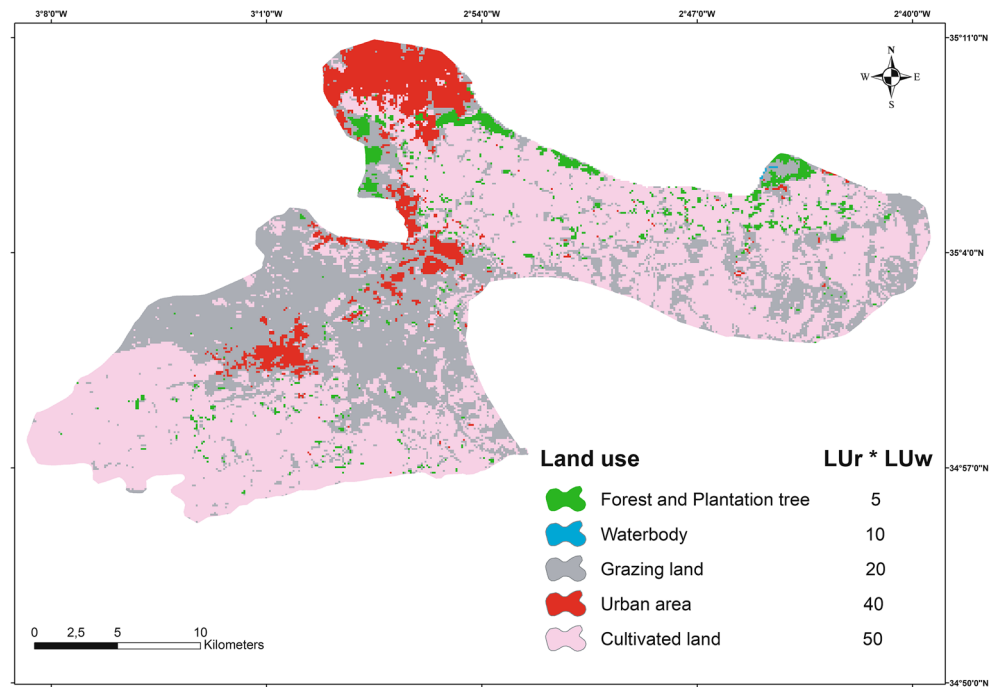


Fig. 4 Depth to aquifer (a), net recharge (b), aquifer media (c), soil media (d), topography (e), impact of vadose zone (f), and hydraulic conductivity (g) maps of Bou-Areg and Gareb aquifers

Fig. 5 Land use classes in the study area



following standard protocol. Nitrate (NO_3^-) was determined by spectrophotometry in the LCME at Cadi Ayyad University. The NO_3^- concentrations ranged between 1.4 and 62 ppm. Electrical conductivity (EC) was measured directly in the field using a conductivity meter. The values of EC ranged from 1922 to 22600 $\mu\text{S}/\text{cm}$ were found.

Results

DRASTIC parameters

To carry out the groundwater vulnerability assessment based on the DRASTIC model, seven parameters were used. The scores and weights of each DRASTIC parameter are shown in (Table 2), ranging from 1 to 10, with the highest values describing higher levels of pollution.

The depth to aquifer (D) map is represented in Fig. 4a. The rate varies from 1.5 to 30 across the whole area and exceeding these values towards the massifs in the west of the plains where values reach up to 110 m. The lower values (< 9 m) were observed in the central and northwestern parts of the Bou-Areg aquifer, and west of the Gareb aquifer, especially in the northwest and southwest of the aquifer. According to the DRASTIC assumptions, these areas are more susceptible to contamination. The higher values (> 30 m) were observed in the eastern part of the aquifers. Moderate values (i.e., 9–30 m) were reported in the other areas. The assigned D ratings vary between 1 and 9, according the classification of Aller

et al. (1987). The highest ratings of 7 and 9 are assigned when the depths are in the classes 4.6–9.1 m 1.5–4.6 m respectively.

The net recharge (R) map is shown in Fig. 4b. The Bou-Areg aquifer has areas with moderate net recharge ranging from 137.3 to 155.04 mm/year for which a score of 6 is assigned. The Gareb aquifer has areas of moderate to high net recharge, ranging from 113.04 in the north to 200 mm/year in the south, rated 6 and 8 respectively.

The aquifer media (A) map is shown in Fig. 4c. In the study area, four types of formations characterizing the aquifer system are clay loam and gravel, conglomerate, the lacustrine limestone, and silt and gravel. A score of 10 is assigned to lacustrine limestone since the permeability value of these carbonate rocks is most likely affected by the presence of karst phenomena (Gleeson et al. 2011; de Graaf et al. 2014; Ouedraogo et al. 2016). Lacustrine limestone is dominant in the Gareb aquifer unlike the Bou-Areg aquifer in which the clay loam and gravel formation is the most dominant, covers the eastern, central, and some of the western parts. A rating of 5 has been assigned to this formation. Conglomerate and silt and gravel are found in both aquifers and are rated 8 and 5 respectively.

From the soil map (S) in Fig. 4d, it can be inferred that limestone silt is the dominant soil type in the study area, followed by clay loam and alluvium. A high rating of 10 was assigned to alluvium because of their high permeability, while a low rating of 3 was assigned to clay loam (Table 2).

The topography map (T) representing the slope of the surface is shown in Fig. 4e. A gentle slope of 0 to 12% dominates

most of the study area. Scores of 10, 9, and 5 were assigned to the classes of these slopes, suggesting that there is a high probability of pollution infiltration. Ratings of 3 and 1 were assigned to the class of 12–18% and > 18% respectively. These two ranges represent a tiny area to the west of the area.

As shown in Fig. 4f, the study area is characterized by three distinct vadose zone materials. This parameter has a major influence on the movement of water into the subsoil (Rahman 2008; Hasan et al., 2019a, b). The silt and gravel formation is the dominant one, assigned a moderate value of 4 and followed by conglomerate and limestone which is the most permeable. The latter is found only at Gareb, and assigned a score of 6 according to Aller et al. The other two formations, clay loam and clay, cover small areas in Bou-Areg, and they rated a score of 3.

The hydraulic conductivity (C) map is shown in Fig. 4g. It is a measure of the aquifer's ability to transmit water when submitted to a hydraulic gradient (Hasan et al., 2019a, b). Hydraulic conductivity in the study area ranges from 14 to 60 (m/day) in the Bou-Areg aquifer and from 30 to 60 (m/day) at the Gareb aquifer. Considering that high conductivity values will be accompanied by high risks of contamination (Rahman 2008), and according to the classification of Aller et al. 1987 (Table 2), the class (12.3–28.7 m/day) received a rating of 4, followed by the class (28.7–41 m/day) which was rated 6, and lastly a rating of 8 was given to the class (41–82 m/day). The latter is the most dominant.

DRASTIC groundwater vulnerability map

DRASTIC index (D_i) was calculated using Eq. (1), covering analysis of the seven thematic maps. The DRASTIC index (Fig. 6a) was classified into 3 classes, based on the quantile classification scheme, to develop the groundwater vulnerability map (Fig. 6b) and to represent low to high vulnerability ranges (Ersoy and Gültekin 2013). The vulnerability scores obtained from the model showed a distribution from 97 to 177. D_i values < 100 represent low vulnerability, 101–140 medium, and 141–200 represent high vulnerability zone. The area covered by each vulnerability class is shown in Table 4. According to the final DRASTIC map, 83.68 % of the study area is classified as moderately vulnerable; this class covers most of the Bou-Areg aquifer and more than half of Gareb. The high vulnerability class covers the second largest area, about 16.26% of the total area, and is mainly present in Gareb, in contrast to Bou-Areg where this class appears only in a small area towards the coast. The low vulnerability class represents only 0.06% of the total surface; it is therefore negligible considering the surface occupied in Bou-Areg (Fig. 6b).

Mapping of groundwater pollution risk

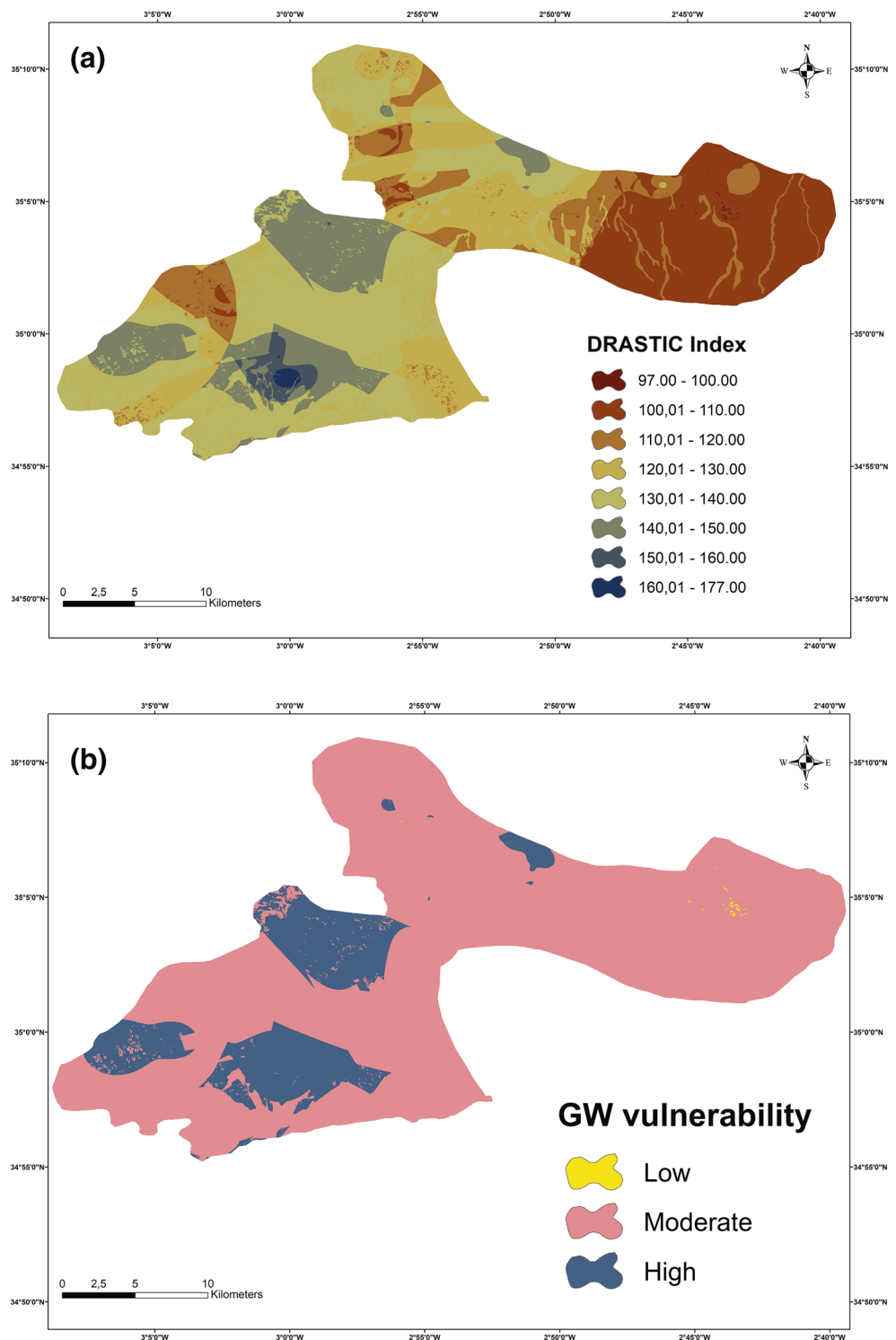
Land use types in the study area are shown in Fig. 5. The study area is divided into five land use categories, forest and plantation tree, waterbody, grazing land, urban and cultivated land. Adding this map to the DRASTIC map following the Eq. (2), we obtained the pollution risk map illustrated in Fig. 7. Pollution risk index values range from 104 to 227. We classified the study area into five zones corresponding to a very low, low, moderate, high, and very high groundwater pollution risk, based on the quantile classification scheme (Pórcel et al. 2014). We observe a very low (104–142) and low risk (142–155) towards the massifs where the slope is slightly higher and the absence of important anthropogenic activities. These classes represent 14.05 and 12.77%, respectively of the total area. High risk (170–182) and very high risk (182–227) areas for pollution in study area are lowlands near urban areas and where agricultural development is important. These classes represent a significant percentage of 21.22 and 21.85% respectively of the total area. Moderate risk to pollution class (155–170) represents 30.11% of the total area (Table 4).

Validation of the specific vulnerability model

As a common pollutant that is introduced into groundwater mainly through fertilizer application, nitrate was chosen because it has a devastating effect on the environment (Diamond and Hodge 2007; Lee 2003; van Beynen et al. 2012). Other studies have recommended that chemicals other than nitrate can be used to quantify groundwater vulnerability (Herlinger and Viero 2007; Jamrah et al. 2008; Srinivasamoorthy et al. 2011; Moratalla et al. 2011; Hasan et al., 2019a, b). In addition to nitrate concentrations, electrical conductivity was also selected as a validation parameter. High EC values indicate high total dissolved solids (TDS) values, which refer to the amount of organic matter, minerals, metals, and salts that are dissolved in a certain volume of water. The spatial distribution of nitrate concentrations in groundwater is shown in Fig. 8a. In the database, 50 water samples were analyzed and indicated nitrate concentration values ranging from 1.38 to 62. Naturally, in groundwater, nitrate (NO_3^-) is present in very low concentrations and its increasing trend indicates contamination by wastewater and nitrogen fertilizers from agriculture use (Hasan et al., 2019a, b). Most values ranging from 25 to 62 ppm are located in the irrigated area, which coincides with highly or moderately vulnerable areas according to the DRASTIC method (Fig. 8a), and in areas with high and very high risk of pollution (Fig. 9a).

The EC in the groundwater samples ranges from 1922 to 122,600 $\mu\text{S}/\text{cm}$. The increase of the electrical conductivity of groundwater (> 750 $\mu\text{S}/\text{cm}$) in areas of high vulnerability

Fig. 6 Intrinsic groundwater vulnerability maps of Bou-Areg and Gareb aquifer (a). Spatial distribution of DRASTIC classes (b)



(Fig. 8b) suggests a contamination of groundwater by industrial wastewater, which is generally rich in total dissolved solids (Hasan et al., 2019a, b). These electrical conductivity values are present in high and very high pollution risk zones (Fig. 9b) that are generally close to urban and agricultural areas; this spatial distribution also supports the previous observation.

Regression of aggregated nitrate and EC concentration data with groundwater vulnerability and risk to pollution

Correlation is a method for scrutinizing the connection between two measurable and continuous variables (Singh et al. 2015). We aggregated the maximum concentration of

Table 4 Classification of the DRASTIC and pollution risk index

Classes	DRASTIC		Pollution risk	
	Range	Area (%)	Range	Area (%)
Very low	-	-	104–142	14.05
Low	97–100	0.06	143–155	12.77
Moderate	101–140	83.68	156–170	30.11
High	141–177	16.26	171–182	21.22
Very high	-	-	183–227	21.85

electrical conductivity and nitrates for each vulnerability class and compared it with vulnerability and pollution risk.

Figure 10a and b indicate that the aggregated maximum nitrate concentration data are positively related to intrinsic vulnerability and pollution risk, with Pearson's correlation coefficient equal to $r = 0.22$ and $r = 0.39$ respectively. A positive Pearson's correlation coefficient value and a significantly higher nitrate concentration in the high vulnerability and pollution risk areas on Fig. 9a also validate the models' results.

Figure 10c and d also indicate that EC is positively correlated to intrinsic vulnerability and pollution risk, for which the Pearson's correlation coefficient is equal to $r = 0.70$ and $r = 0.73$ respectively. These high values provide a good correlation.

Discussion

This study is one of the first global efforts to identify aquifers in northern Morocco that are under acute threat of contamination by agricultural activities and industrial effluents. As already mentioned, El Yaouti et al. (2009) and Re et al. (2013) have carried out studies on the water quality of the Bou-Areg aquifer; however, there is no research on the Gareb aquifer dealing with water quality. Based on the results of the nitrate and EC analyses, the quality of Gareb's groundwater is as degraded as that of Bou-Areg. In this study, we have deployed the original DRASTIC model proposed by Aller et al. (1985), carrying out an intrinsic vulnerability study. The vulnerability scores obtained from the model showed a distribution from low to high vulnerability. The DRASTIC groundwater vulnerability map of the study area (Fig. 6) indicates that areas with gentle slopes (0–6%) and shallow aquifers (1.5–15 m), including gravel, conglomerate, and limestone have the highest vulnerability indices. Similar studies conducted by Bojórquez-Tapia et al. (2009), Saidi et al. (2011), and Hasan et al. (2019a, b) have also identified the depth to aquifer as one of the most influential parameters. Other researchers have modified the DRASTIC model by either adding or removing one or more parameters, depending on the case it treats (Hao et al. 2017; Li et al. 2017; Singh et al. 2015). In order to identify the areas at risk of pollution, the original DRASTIC model was modified using the additive model of Secunda et al. (1998) by adding the parameter

Fig. 7 Groundwater pollution risk for the study area

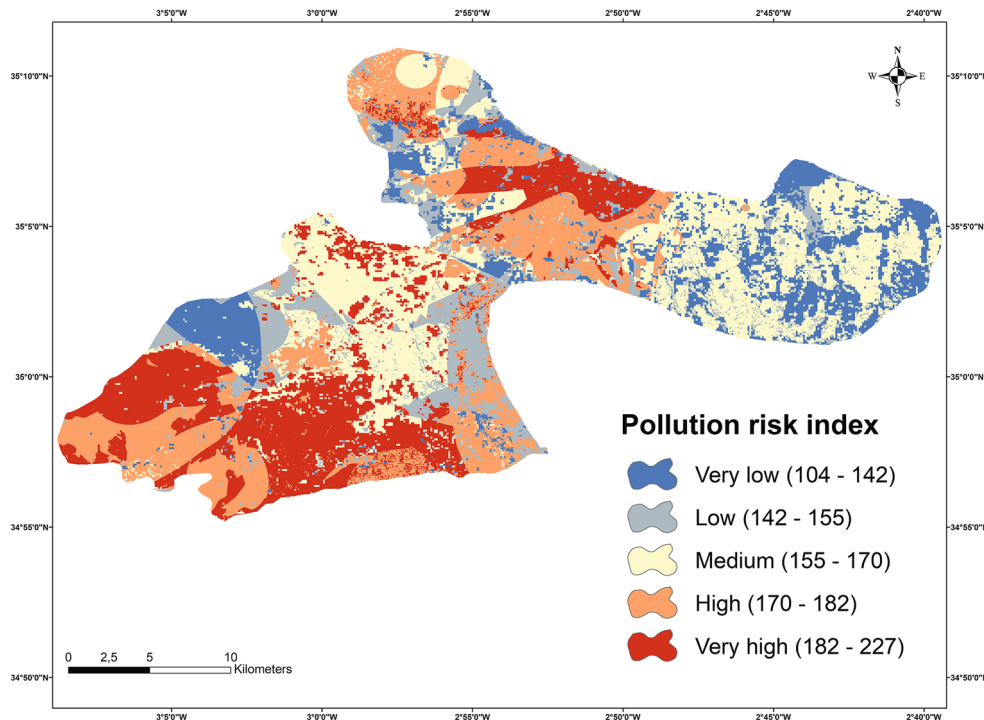
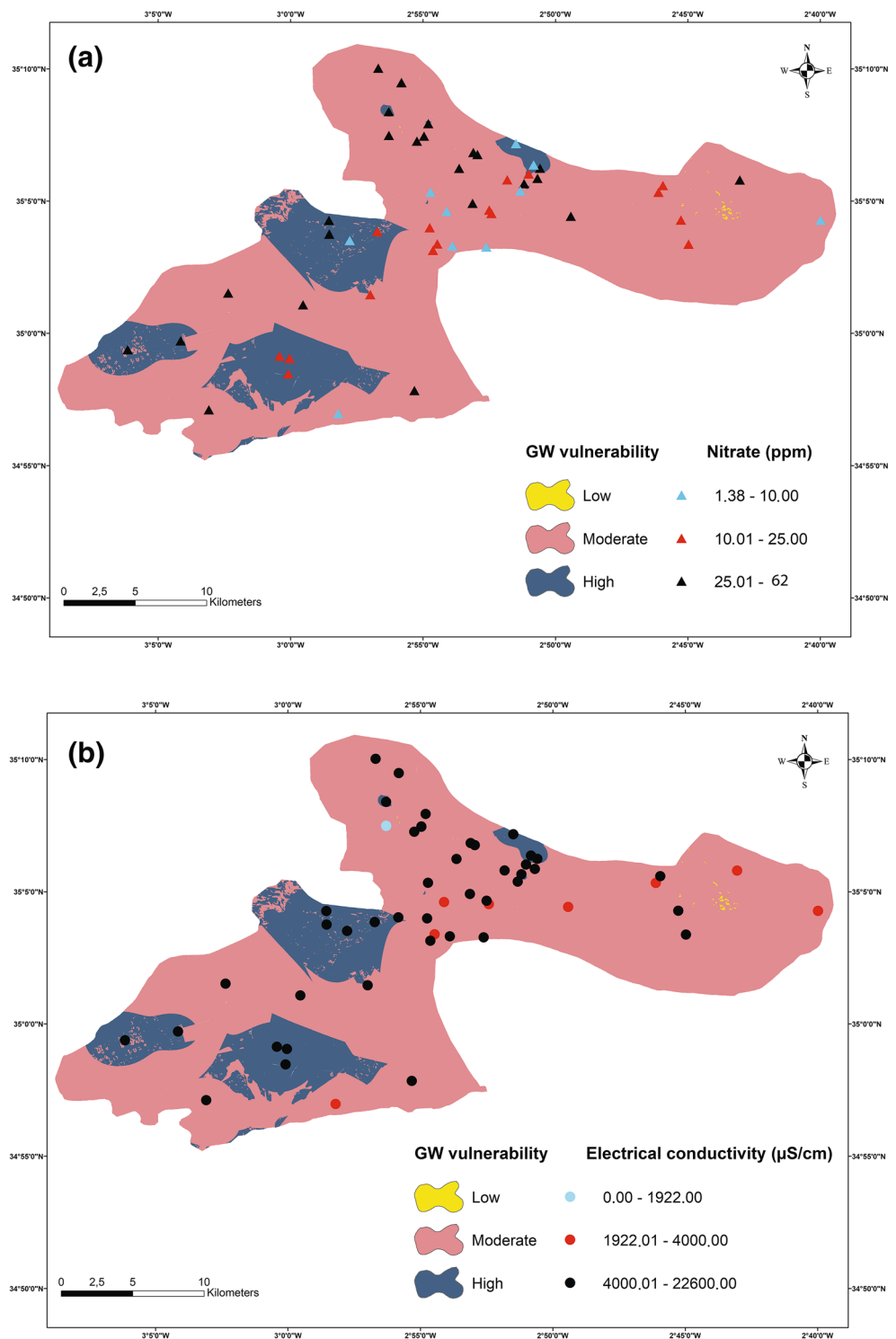


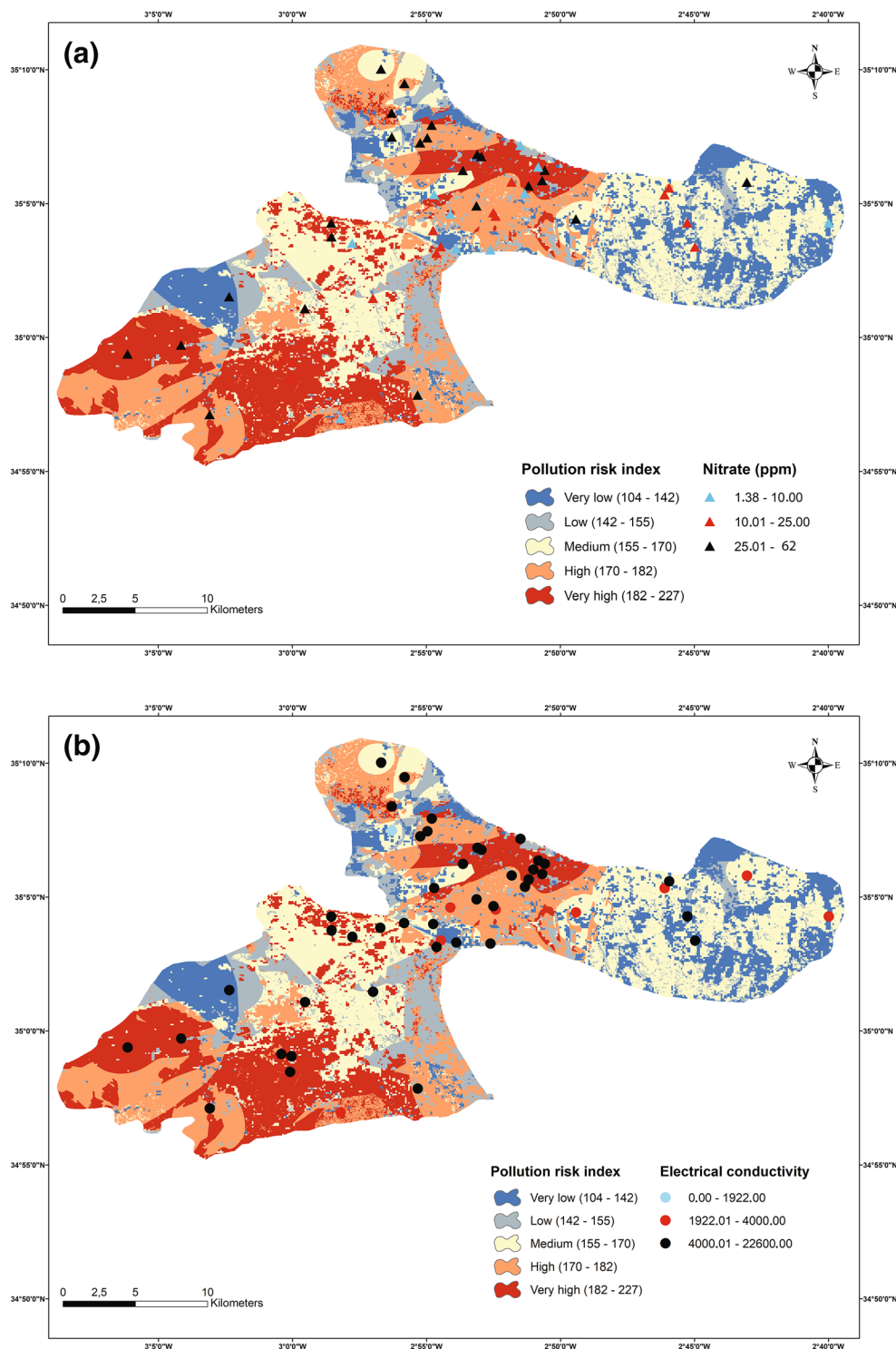
Fig. 8 Spatial distribution of DRASTIC intrinsic vulnerability with **a** nitrate concentrations and **b** electric conductivity



describing the type of land use, which has been applied in several studies and has shown its effectiveness (Secunda et al. 1998; Dixon 2005; Ouedraogo et al. 2016). Land use types were not considered as a contaminant loading indicator in groundwater vulnerability, but as the main factor affecting the fate and processing of nitrate in the vadose zone. Purification process, vertical infiltration, and microbial

process of the pollutant will apparently differ depending on the different types of land use, since each land use has its own soil nutrients and microorganisms. Hence, the type of land use should be considered to be an index of groundwater vulnerability for better prediction of vulnerable zones considering the local influencing factors (Huan et al. 2012; Busico et al. 2017; Garewal et al. 2017). The risk of groundwater to

Fig. 9 Groundwater pollution risk for the study area with **a** nitrate concentrations and **b** electrical conductivity



contamination in study area is characterized by high to very high-risk levels where hazards are located. Agricultural activities that occupy large part of the groundwater basin are mainly concentrated in the center of the Bou-Areg plain and south of the Gareb plain, resulting in high risks due to the high vulnerability of these areas. The low depth of groundwater, gentle slopes, and the high recharge in these areas combined

with agricultural activities and near urban areas explain this high pollution risk. Moderate pollution risk is most prevalent in areas where geological formations are highly permeable but no significant land use is involved. A region with low and very low pollution risk does not mean that it is free of groundwater pollution, but that it is relatively less susceptible to contamination than other regions. This finding is similar to the

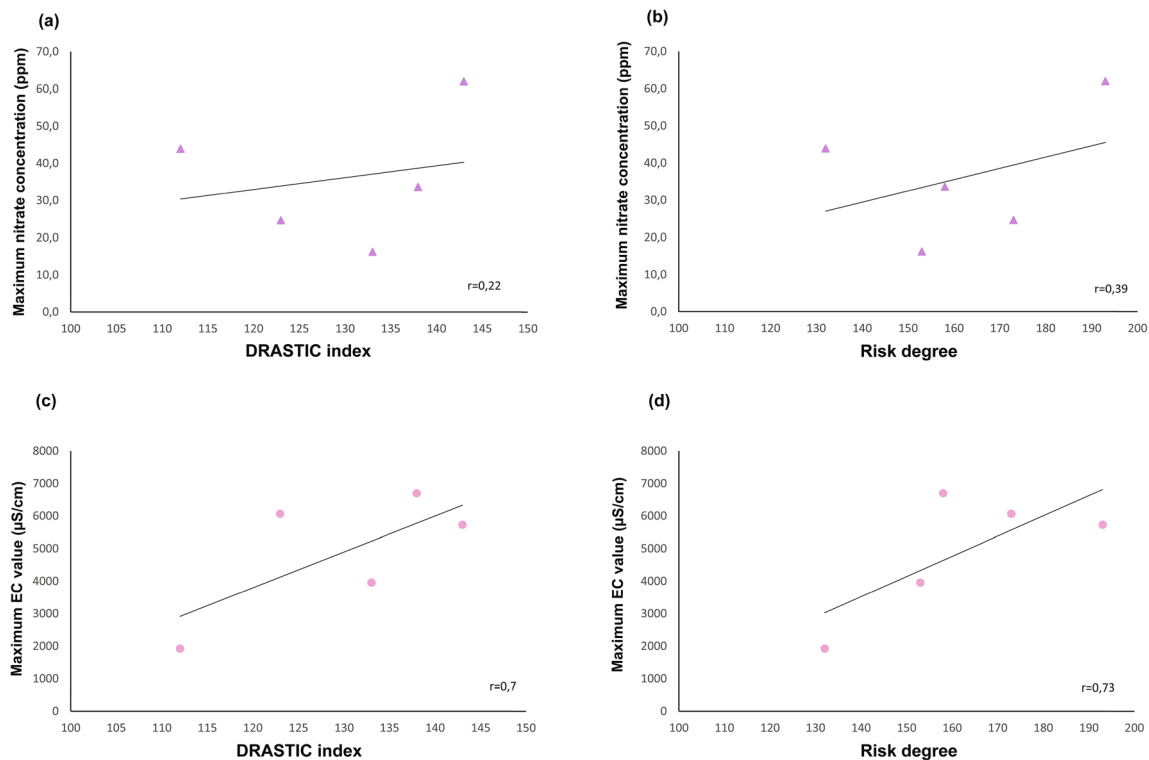


Fig. 10 Plots of DRASTIC index (a) and pollution risk (b) versus nitrate maximum concentrations. Plots of DRASTIC index (c) and pollution risk (d) versus electrical conductivity maximum concentrations

corresponding studies in other parts of the world (Shrestha et al. 2016, Kozłowski and Sojka 2019; Ckakaraboty et al. 2007; Rahman 2008; Srinivasamoorthy et al. 2011) and to the corresponding study conducted by Ouedraogo et al. (2016) in Africa, which revealed that the coastal areas, including the north of Morocco, have a high vulnerability and pollution risk. The same study conducted by Ouedraogo et al. (2016) found that in southern Morocco, the vulnerability index and pollution risk decrease compared to the north; this was also confirmed by the study conducted by Heiß et al. (2020), showing a low groundwater vulnerability and a medium risk to pollution.

Numerous models have been used by different authors to validate the results of vulnerability maps (Barbulescu 2020). Kumar et al. (2015) noted that this comparison is not encouraged because various approaches utilize different parameters; hence, the vulnerability maps might not be comparable. Validation of vulnerability maps on contaminant datasets collected on-site from wells distributed throughout the study area is commonly applied. This is generally conducted using nitrate concentrations in the collected samples. Anthropogenic contamination from farming, especially nitrate pollution, is a major concern in groundwater management, particularly in arid and semi-arid areas where agriculture is one of the most important economic activities (Malki et al. 2017). Because of its absence or very low presence in groundwater under normal conditions, as well as its devastating effect on the

environment, nitrate has been selected for model validation, and because high EC values indicate high total dissolved solids (TDS) values, which refer to the amount of organic matter, minerals, metals, and salts that are dissolved in a certain volume of water, it was selected as a second validation parameter. A higher concentration of nitrates in areas of high vulnerability and high pollution risk allows the validation of model results. The wells with high nitrate concentrations have a low water depth, which explains the nitrate content present in these shallow wells, which, combined with the permeable formations of the vadose zone, cause a faster passage of nitrates from the soil to the groundwater. The increasing trend of EC of groundwater (> 750 µS/cm which is the maximum value recommended by WHO) throughout the study area suggests a contamination of groundwater by wastewater from industries, which are generally rich in TDS (Hasan et al., 2019a, b). The spatial distribution of the EC with high values in the areas of high and medium vulnerability and pollution risk on groundwater vulnerability supports this observation.

When validating the pollution risk on an independent dataset, we observe that the pollution risk map is more consistent with the observed nitrate and EC concentrations than the vulnerability map (the Pearson’s correlation coefficient increases). This demonstrates that the pollution risk map provides useful spatial information for decision making at the regional scale. The pollution risk model is, therefore, an appropriate tool to support groundwater resource management,

groundwater quality protection, and land use planning at the scale of the Gareb and Bou-Areg groundwater bodies. The concentrations of electrical conductivity and nitrates indicate that the water quality in the study area is degraded and although the vulnerability and risk of pollution is high, it is nevertheless possible to reduce or limit it, while controlling intensive pumping in the coastal zone to avoid water salinity, optimizing fertilizers and pesticides, and controlling domestic and agricultural discharge points (van Beynen et al. 2012).

Conclusion

The water quality issue is now one of the 17 sustainable development goals of the United Nations to be attained by 2030 where decreasing pollution and minimizing the release of hazardous chemicals is a major priority to achieve universal and equitable access to safe drinking water. To adequately plan and manage groundwater resources, it is necessary to delineate vulnerable areas and identify the source of contaminants. Hence, this study implemented a DRASTIC and pollution risk models to delineate and identify the spatial extent of vulnerability and pollution of the Gareb and Bou-Areg aquifers.

The results of the study showed that the vulnerability range from lower vulnerable to highly vulnerable level. Almost all (99.94%) of the study area is in “moderate” and “high” vulnerability areas, 83.68% and 16.26% respectively for each class. These areas are more susceptible to pollute groundwater. The groundwater of Gareb is relatively more vulnerable to pollution than that of Bou-Areg.

The DRASTIC model has been commonly used for more than 20 years to assess the intrinsic vulnerability of an aquifer. Nevertheless, intensive human activities modify the surface natural environment, which has a significant influence on the underground environment. Overcoming this problem, the improved pollution risk model, which combines intrinsic vulnerability and land use, has been used to determine risk to pollution in the study area. The pollution risk index ranked the area under five classes, of which the very high, high, and medium classes cover 73.18% of the area. These zones have a gentle slope close to urban areas and where agricultural development is important.

When validating DRASTIC and the modified model of DRASTIC which is the pollution risk on an independent dataset, we observe that the pollution risk map is more consistent with the nitrate concentrations and EC concentrations than the vulnerability map. This demonstrates that the pollution risk map provides useful spatial information for decision making at the regional scale.

In view of the vast areas of poor groundwater quality, areas at high and moderate risk of contamination must be strictly protected. Managing the impacts of agricultural return flows and urban inputs will improve groundwater quality, with relevant positive effects on crop efficiency, soil salinization, and

environmental problems. The pollution risk map gives priority to environmental management and land use planning, which are important for the sustainable development of this region.

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Mohammed Elgettafi: Conceptualization, Fieldwork, Methodology, Resources, Investigation, Supervision, Writing-review & editing.

Mahjoub Himi: Conceptualization, Investigation, Resources, Supervision, Writing-review & editing.

Albert Casas: Conceptualization, Investigation, Resources, Supervision, Writing-review & editing.

Rim Tijani: Conceptualization, Methodology, Resources, Writing, Mapping.

Fatima Azzahra El khantouri: Conceptualization, Methodology, Resources, Writing, Mapping.

Declarations

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Competing interests The authors declare that they have no competing interests.

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