

Assessment of groundwater vulnerability and quality in coastal aquifers: a case study (Tipaza, North Algeria)

A. Bouderbala¹  · B. Remini² · A. Saaed Hamoudi³ · A. Pulido-Bosch⁴

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Abstract In the coastal aquifer of Nador, aquifer vulnerability index (AVI) and Groundwater occurrence, Aquifer hydraulic conductivity, Level above sea, Distance from the shore, Impact magnitude of the existing seawater intrusion in the area, Thickness of the aquifer which is being mapped (GALDIT) methods were employed to determine the groundwater vulnerability to anthropogenic pollution and seawater intrusion. The groundwater quality is also studied by using water quality index (WQI), for identify sectors with the best quality for drinking purposes. The AVI method classified the area into three vulnerability classes: low, moderate, and high vulnerability in the two parts of Nador valley due to anthropogenic activities, while the GALDIT method delineates the area into three vulnerability classes: low (<5), moderate (5–7.5), and high (>7.5) covering 47, 36, and 17 %, respectively, of the study area surface. The high class is located in the coastal sector; it is due to the proximity to the sea, the high hydraulic conductivity of aquifer, the exchange freshwater-seawater after the overexploitation, and also the thickness of the aquifer. WQI has been calculated in the present study to assess suitability of groundwater for drinking purposes. Twenty-four groundwater samples were collected from the Nador plain during the dry period of 2013. The WQI show

that 17 % of groundwater sample falls in good water category, 46 % falls in poor water category, 12 % falls in very poor water category, and 25 % falls in unsuitable water category. The groundwater unsuitable for drinking purposes is due to its high salinity, with high values of EC, Cl^- , Na^+ , Mg^{2+} , and SO_4^{2-} due to the seawater intrusion.

Keywords Groundwater quality · Coastal aquifer · Vulnerability · GALDIT · AVI · WQI

Introduction

Coastal Mediterranean aquifers constitute a major source for freshwater supply in many cities around the world, especially in the scarce rainfall zones. In these coastal zones, the anthropogenic activities are increased particularly during the summer, the period associated with considerable tourist activity; this creates the need for freshwater even more. Indeed, the groundwater resources are threatened by overexploitation with increase in pumping, therefore the possibility of contamination by seawater. So, salinization of coastal aquifer has been experienced recently as a major constraint imposed on groundwater utilization, and therefore one of the most important water pollution problems (Pulido-Bosch 2014). As far as the groundwater vulnerability, it is defined as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer (Lobo-Ferreira et al. 2003). The intrinsic vulnerability is usually considered as a property of a groundwater that depends on its sensitivity to human and/or natural impacts. Once identified, these vulnerable areas can be targeted by careful land-use planning, intensive monitoring, and by contamination prevention of groundwater (Babiker et al. 2007; Jayasingha et al. 2011). Since then, several studies on this issue have been published (Foster 1987; Adams

✉ A. Bouderbala
bouderbala.aek@gmail.com

¹ Department of Earth Sciences, University of Khemis Miliana, Khemis Miliana 44000, Algeria

² Department of Water Sciences, University of Blida, Blida 9000, Algeria

³ Department of Hydraulic, University of Chlef, Chlef 2000, Algeria

⁴ Department of Biology and Geology (Hydrogeology), University of Almeria, Almeria, Spain

and Foster 1992; Robins et al. 1994; Hötzel 1996; Daly and Drew 1999) and various methods have been proposed to map the vulnerability of aquifers to contamination (Gogu and Dassargues 2000; Awawdeh and Jaradat. 2010; Saidi et al. 2010; Fandi and Alyazjeen 2013; Alam et al. 2014; Jilali et al. 2015; Shekhar et al. 2015). Among these methods are DRASTIC (Aller et al. 1987), GOD (Foster 1987), aquifer vulnerability index (AVI) (Van Stempvoort et al. 1993), SINTACS (Civita and De Maio 1997), Groundwater occurrence, Aquifer hydraulic conductivity, Level above sea, Distance from the shore, Impact magnitude of the existing seawater intrusion in the area, Thickness of the aquifer which is being mapped (GALDIT) (Chachadi et al. 2003), and PI (Nguyet and Goldscheider 2006). The name attributed to each of these methods is an acronym of the parameters deemed most important in evaluating vulnerability to contamination.

Water quality index (WQI) is one of the most effective tools to communicate information on the quality of water (Pradhan et al. 2001; Adak et al. 2001). It thus becomes an important parameter for the assessment and management of groundwater. WQI was used to determine the suitability of the groundwater for drinking purposes (Mishra and Patel 2001; Naik and Purohit 2001; Avvannavar and Shrihari 2008; Sahu and Sikdar 2008). It is calculated from the suitability of groundwater for a specific purpose basing on the standards for drinking purposes as recommended by WHO (WHO 2008).

In this study, two methods, AVI and GALDIT, have been suggested for groundwater vulnerability assessment to pollution, in particular, from surface like nitrates and by seawater intrusion along the coastal area. The obtained vulnerability maps via these methods are compared with the approach of WQI. This work presents the application of AVI, GALDIT, and WQI in the coastal aquifer of Nador in order to identify the parts of the aquifer that are more vulnerable to contamination from the two sources (anthropogenic pollution and seawater intrusion).

Study area

The study area is located approximately at 75 km west of Algiers. It is limited to the north by the Mediterranean Sea, to the south and east by the slopes of the Sahel, and to the west by the Chenoua massif, with a total surface of 20 km² (Fig. 1). This region has a Mediterranean semi-arid climate, with large temperature and rainfall variations. Averages of annual temperature and rainfall are about 18 °C and 540 mm, respectively (period 1988–2013, Boukourdane station). The morphology of the study area is characterized by slopes of between 0 and 1 %, while the slopes of the hills and piedmont, in the east (slopes of the Sahel) and the west (Chenoua massif), have gradients of between 1 and 10 %. The coastal population of these towns is around 45,000 inhabitants according to the 2008 census.

The geology of the study area is occupied by Pliocene and Quaternary terrains (Bouderbala and Remini 2014). The Pliocene terrain is represented by Plaisancian clayey marl, overlying Astian limestone and sandstone. The basement of the Pliocene aquifer is formed by a very thick layer of low-permeability clayey marl. Meanwhile, the aquifer itself is characterized by high permeability, with values of up to 6.8×10^{-4} m/s, an average saturated thickness of 60 m, and a transmissivity value of about 2.0×10^{-2} m²/s. The Quaternary terrains are formed by clay, sand, and gravel, reaching a thickness of 30 m in the center of the plain. Their permeability is about 10^{-3} m/s and the transmissivity is 10^{-2} m²/s. There are local deposits of clay and sandy clay overlying all these materials.

The Plio-Quaternary aquifer is partially confined by Quaternary formations (clay, gravel, and sand) in the center and downstream of plain, but it's unconfined in the other sector of the plain where the outcrops appear. The impervious substratum, as already indicated, is formed by clay and marl of Pliocene age.

The water table is located at a depth of only a few meters in downstream, but it is at more than 10 m in upstream of the plain. Most of the recharge of this Plio-Quaternary aquifer comes from the rainfall infiltration on the outcrops of the plain. The recharge occurs also by irrigation return flow. Recharge by the Wadi Nador is much reduced because the banks of the watercourses are clogged with clay. However, the axis of the synclinal nearly coincides with the flow trajectory of Wadi Nador (Bouderbala et al. 2014; Bouderabala 2015).

The analysis of the piezometric map related to the period of high water (April 2012) shows that the lines of groundwater flows converge towards the axis of the synclinal furrow, which constitutes the principal drainage axis of the Plio-Quaternary aquifer. It also indicates the existence of the piezometric water level "0 m" inside the plain; probably, this is related to over-exploitation of groundwater in this coastal sector, which generates a mixture between marine water and groundwater.

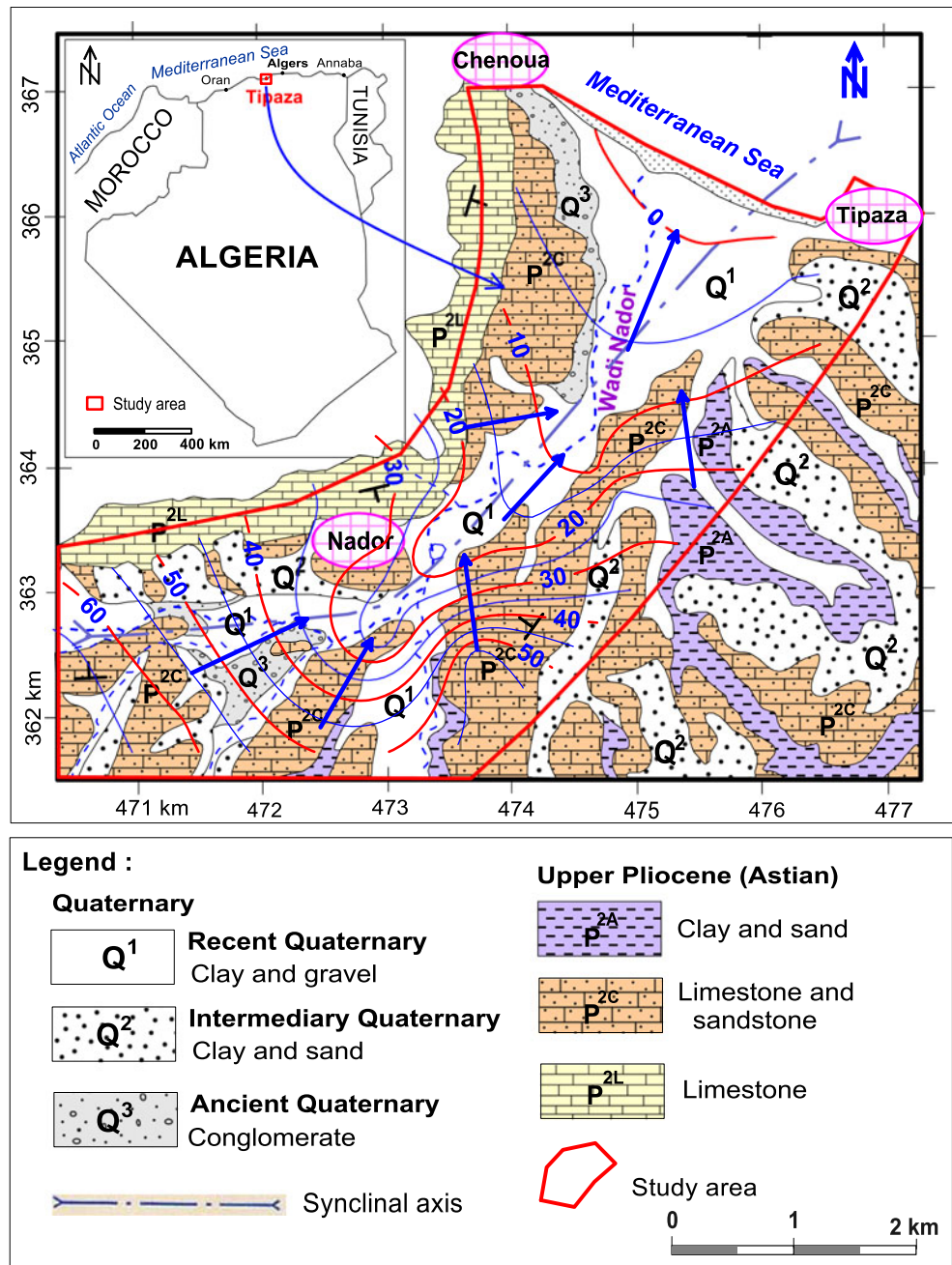
Methodology

The study is based on the obtained measurements from the field surveys that were conducted during the hydrological year 2013 and supplemented by the compilation of the information collected from various technical services charged of the management of groundwater of this aquifer (National Hydraulic Resource Agency, Hydraulic and Agricultural Directions, Algerian company of water, National Sanitation Office, and National Office of the Irrigation and Drainage).

Groundwater vulnerability assessment

The methods of groundwater vulnerability assessment are based on the information about the following: the soil of

Fig. 1 Geological map of the study area



unsaturated zone, recharge conditions, and aquifer characteristics. They are classified into two approaches: the first approach aims to protect groundwater from general pollution using only physical parameters “intrinsic vulnerability” (as AVI method). The second approach deals with vulnerability to seawater intrusion using a combination between physical and chemical parameters (as GALDIT method).

Intrinsic vulnerability

AVI developed in Canada (Van Stempvoort et al. 1993), name stands for aquifer vulnerability index, was developed to

estimate the aquifer vulnerability to contamination from potential sources at or near the ground surface. This method quantifies vulnerability by hydraulic resistance to vertical flow of water through the protective layers. This can be used as a rough estimate of vertical travel time of water through the unsaturated layers; however, important parameters controlling the travel time as hydraulic gradient, diffusion, and sorption are not considered here (Kirsch 2009). It is a numerical method that uses two parameters: the thickness of each sedimentary layer above the uppermost saturated aquifer surface (*d*) and the estimated hydraulic conductivity (*k*) of each of these sedimentary layers above the water table. The thickness (*d*) of

sedimentary layers (e.g., gravel, sand, and marl) is obtained from logs of wells. So, the hydraulic resistance C is referred to a combination of two parameters. This parameter C is a theoretical factor used to describe the resistance of an aquitard to vertical flow. It has dimension time. The calculated C or $\log(C)$ values can be used directly to generate iso-resistance contour maps (Tables 1 and 2). AVI determines the average vulnerability index from the hydraulic resistance, in years or days. It is calculated by means of the following expression:

$$C = \sum di/ki,$$

where di and ki are thickness (m) and hydraulic conductivity of each protective layer (m/day), respectively.

Vulnerability to seawater intrusion

GALDIT method, developed in India, is used in the object to delineate the most vulnerable areas to seawater intrusion. The parameters of the seawater intrusion were described by Chachadi and Lobo-Ferreira 2001.

Each of GALDIT factor is evaluated by respecting the other; this with an aim of determining the importance of each parameter. Several studies have applied this method successfully (Chachadi and Lobo-Ferreira 2001; Chachadi 2005; Lobo-Ferreira et al. 2005; Kallioras et al. 2006, 2011).

GALDIT index can predict the aquifer's vulnerability to seawater intrusion by combining hydrogeological data, describing the state of the aquifer under investigation and categorizing the data into different parameters, which are rated and weighted according to their relative significance, and finally combined in the GALDIT equation. Chachadi and Lobo-Ferreira (2001) realized the necessity for developing a numerical ranking system to assess the general seawater intrusion potential of each hydrogeologic context. In this sense, it was concluded that the most important factors that control the seawater intrusion (Chachadi et al. 2002; Lobo-Ferreira et al. 2005; Chachadi and Lobo-Ferreira 2001; Recinos et al. 2015) are: *groundwater* occurrence (aquifer type; unconfined, confined, or leaky confined), *aquifer* hydraulic conductivity, depth to ground water *level* above sea, *distance* from the shore (distance inland perpendicular from shoreline), *impact* magnitude of the existing seawater intrusion in the area, *thickness* of the aquifer which is being mapped. Each of the six parameters has a predetermined weight that reflects its relative importance to seawater vulnerability.

Table 1 Rating values of the hydraulic conductivity (k) parameter for the AVI method (Van Stempvoort et al. 1993; Rodriguez et al. 2001)

Lithology	Gravel	Sand	Silt sand	Silt	Clay	Sand silt clay
k (m/day)	10^3	10	1	10^{-1}	10^{-4} - 10^{-3}	10^{-5}

The GALDIT index is given by the following equation (Chachadi and Lobo-Ferreira 2001):

GALDIT index

$$= (1 \cdot G + 3 \cdot A + 4 \cdot L + 4 \cdot D + 1 \cdot I + 2 \cdot T) / 15.$$

The most significant indicators for saltwater intrusion have a maximum weight of 4 and the least have a minimum weight of 1. The importance ratings range between 2.5 and 10. This gives a minimum value of the GALDIT index of 1 and the maximum value of 15. The parameters of GALDIT method are shown in the Table 3.

Groundwater quality assessment

Groundwater quality depends on the quality of recharged water, atmospheric precipitation, inland surface water, and on sub-surface geochemical processes (Sadat-Noori et al. 2014). The WQI map can be used as a monitoring tool for groundwater quality. Moreover, this map aims to rapidly distinguish the location of most and least suitable water for drinking in the study area concerned to its water mineral content. By mapping the index, the areas of high- and low-water quality can easily be distinguished by some researchers as well as decision-makers and/or the general public. In addition, an important contribution for understanding relationships between land use and groundwater quality, groundwater depth, and groundwater quality are provided (Backman et al. 1998; Avvannavar and Shrihari 2008; Rizwan and Gurdeep 2010). WQI is defined as a technique of rating that provides the composite influence of individual water quality parameter on the overall quality of water. It is calculated from the point of view of human consumption (Saeedi et al. 2010; Ketata et al. 2012; Sadat-Noori et al. 2014). The standards for drinking purposes as recommended by WHO (2008) for the calculation of WQI.

Water samples were collected in September 2013 from 24 wells over the study area. They were collected in clean polyethylene bottles. These later were thoroughly rinsed with the groundwater to be sampled. The water samples were collected after pumping for 30 min. All the samples

Table 2 Relationship of aquifer vulnerability index to hydraulic resistance (Van Stempvoort et al. 1993)

Hydraulic resistance C	Log(C)	Vulnerability (AVI)
0 to 10	<1	Extremely high
10.1 to 100	1 to 2	High
100.1 to 1000	2 to 3	Moderate
1000.1 to 10000	3 to 4	Low
>10000	>4	Extremely low

Table 3 Parameters of GALDIT method (Chachadi 2005)

Parameters	Weight	Indicator variables		Importance rating
		Class	Range	
Groundwater occurrence/aquifer type	1	Confined aquifer		10
		Unconfined aquifer		7.5
		Leaky confined aquifer		5
		Bounded aquifer (recharge and/or impervious boundary aligned parallel to the coast)		2.5
Aquifer hydraulic conductivity in meters per day	3	High	> 40	10
		Medium	10–40	7.5
		Low	5–10	5
		Very low	<5	2.5
Height of groundwater level above sea level in meters	4	High	<1.0	10
		Medium	1.0–1.5	7.5
		Low	1.5–2.0	5
		Very low	>2.0	2.5
Distance from the shore/high tide in meters	4	High	<500	10
		Medium	500–750	7.5
		Low	750–1000	5
		Very low	>1000	2.5
Impact of existing status of seawater intrusion [$\text{Cl}^-/(\text{HCO}_3^- + \text{CO}_3^{2-})$]	1	High	>2.0	10
		Medium	1.5–2.0	7.5
		Low	1.0–1.5	5
		Very low	<1.0	2.5
Thickness of aquifer being mapped (saturated thickness in meters)	2	High	>10	10
		Medium	7.5–10	7.5
		Low	5–7.5	5
		Very low	<5	2.5

were stored in an ice chest at a temperature lower than 4 °C and later transferred to the laboratory for the analysis. In situ, measurements included electrical conductivity (EC), TDS, pH, and temperature were taken using a portable field kit, since these parameters changes with the storage time. For major chemical ions, analysis (Cl^- , SO_4^{2-} , HCO_3^- , NO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , and K^+) was performed at the laboratory of the National Agency of Hydraulic Resources, in Algeria. Major ions like chlorides and bicarbonates were analyzed using volumetric methods. Calcium, magnesium, sodium, and potassium were analyzed using atomic adsorption spectrometry. Nitrates were measured by a colorimetric method. Sulphates were estimated by the UV–visible spectrophotometer. The ion balance error was computed, taking the relationship between the total cations and the total anions for each complete analysis of water samples. All the water quality parameters were expressed in milligrams per liter, except EC which was expressed in μScm^{-1} .

In order to obtaining WQI map, the results are treated with in the Geographic Information System (GIS) environment.

Ten parameters (EC, pH, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- , and NO_3^-) from the dry period 2013 analysis data have been chosen for drinking water classification. All the analyses are observed within the range of acceptability ($\pm 5\%$).

For computing WQI, three steps were followed (Dwivedi and Pathak 2007; Asadi et al. 2007; Vasanthavigar et al. 2010; Saeedi et al. 2010; Yidana and Yidana 2010). In the first step, each of the ten parameters has been assigned a weight (w_i) based on their perceived effects on primary health. The maximum weight of 5 has been assigned to parameters like EC, chloride, sulfate, sodium, magnesium, and nitrate due to their major importance in water quality assessment. Bicarbonate is given the minimum weight of 1; it plays an insignificant role in the water quality assessment. Other parameters like calcium and potassium were assigned with a weight between 1 and 5, depending on their importance in the overall quality of water for drinking purposes (Srinivasamoorthy et al. 2008; Ketata et al. 2011) (Table 4).

Table 4 Vulnerability categories classes of GALDIT method (Chachadi 2005)

Class vulnerability	Extremely low	Low	Moderate	High
Index	<2.5	2.5–5	5–7.5	>7.5

In the second step, the relative weight (Wi) of each parameter is computed using equation:

$$Wi = \frac{wi}{\sum_{i=1}^n wi},$$

where (wi) is the weight of each parameter, (n) is the number of parameters, and (Wi) is the relative weight.

The third step, a quality rating scale (qi), is calculated for each parameter using equation:

$$qi = \frac{Ci}{Si} \times 100,$$

where (qi) is the quality ranking, (Ci) is the concentration of each chemical parameter in each water sample in milligrams per liter, and (Si) is the WHO standard for each chemical parameter in milligrams per liter. The WQI is determined for each chemical parameter using equation:

$$WQI = \sum_{i=1}^n Wi \times qi,$$

where (qi) is the rating based on concentration if (i th) parameter and (n) is the number of parameters. Computed WQI values are usually classified into five categories (Table 5): excellent, good, poor, very poor, and unsuitable for human consumption (Sahu and Sikdar 2008).

In this study, GIS has been used in the interpolation of the different parameters used in all methods, using the software Surfer 10 and MapInfo 7. It is used as a database system in order to prepare different layers of maps to locate vulnerable areas and to find out the spatio-temporal behavior of the groundwater quality based on the norms for drinking water.

Table 5 Classification of groundwater quality according to WQI (Sahu and Sikdar 2008)

WQI	Type of water
<50	Excellent water
50–100	Good water
100.1–200	Poor water
200.1–300	Very poor water
>300.1	Water unsuitable for drinking purpose

Results and discussions

Vulnerability assessment

AVI method

The resulting aquifer vulnerability map indicates three classes in relation to each degree of vulnerability according to the classification of Van Stempvoort et al. (1993) (Tables 2 and 6, Fig. 2).

The distribution of aquifer vulnerability is characterized between high and low vulnerability. There is a significant change in the pattern AVI zones between the north, central, and south areas. This change is due to the heterogeneity of the superficial geology of the area (land of surface). The lowest classes of vulnerability (AVI >1000 days) cover 19 % of the total study area surface and are essentially due to the thick sediments of the unsaturated zone, the low hydraulic conductivity, and the low recharge rate. These parameters control the attenuation of the contaminated material into the aquifer. The moderate vulnerability (100 < AVI < 1000 days), which is represented by 37 % of the total surface, is due to the moderate thickness sediments of the unsaturated zone and to the moderately deep of water table, while the high vulnerability (AVI < 100 days), which is represented by 44 % of the total surface, in the east and west of the Nador plain is due to the high hydraulic conductivity of unsaturated zone, which is constituted essentially by Astian limestone and sandstone, where the contaminants attain rapidly the water table. It is noted that the aquifer vulnerability map generated by the AVI method can be influenced by the density of wells.

The analysis of the hydrogeologic cross-sections, using the results of the drilling logs, shows that the unsaturated zone in the two parts of Nador aquifer are generally constituted by limestone and sandstone with high hydraulic conductivity which facilitates its contamination from the surface; while in opposite, the unsaturated zones in the coastal and center zones of plain have low hydraulic conductivity which make aquifer on low vulnerability from surface.

GALDIT method

The six GALDIT index parameters were employed to determine the seawater vulnerability of the Nador aquifer were (Table 7):

Parameter G Groundwater occurrence represents the aquifer type of the study area. For the case of the area under investigation, the aquifer is considered as unconfined-to-confined aquifer. The confining layer being composed of sandstone and limestone under the clay, hence the rating value for this

Table 6 Vulnerability class according to AVI index

Samples	d_1 (m)	k_1 (m/day)	d_2 (m)	k_2 (m/day)	AVI index	Vulnerability class
199	5.3	0.001	5	1000	5300.01	Low vulnerability
200	6	0.001	14.8	1000	6000.01	Low vulnerability
198	2	0.001	2.8	1000	2000.00	Low vulnerability
191	0.5	0.001	1	1000	500.00	Moderate vulnerability
148	8	0.01	2.15	1000	800.00	Moderate vulnerability
149	8	0.01	3.6	1000	800.00	Moderate vulnerability
184	0.9	0.01	9.6	1000	90.01	High vulnerability
193	0.9	0.01	3	1000	90.00	High vulnerability
143	3.5	0.04	–	–	87.50	High vulnerability
146	2	0.1	13.5	1000	20.01	High vulnerability
147	2.5	0.02	7.24	1000	125.01	Moderate vulnerability
134	3	0.1	3.3	1000	30.00	High vulnerability
133	2	0.1	2.2	1000	20.00	High vulnerability
33	1.8	0.1	3.93	1000	18.00	High vulnerability
32	1.8	0.1	3.93	1000	18.00	High vulnerability
142	2	0.01	1.5	1000	200.00	Moderate vulnerability
153	4.4	0.001	–	–	4400.00	Moderate vulnerability
153B	4.3	0.001	–	–	4300.00	Moderate vulnerability
127B	2.5	0.001	–	–	2500.00	Moderate vulnerability
127	2.3	0.001	–	–	2300.00	Moderate vulnerability
13	3.5	0.001	–	–	3500.00	Moderate vulnerability
CRF	3.5	0.001	–	–	3500.00	Moderate vulnerability
161	3	0.1	3.5	1000	30.00	High vulnerability
161B	3	0.1	3.4	1000	30.00	High vulnerability

Fig. 2 Groundwater vulnerability of the Nador aquifer using AVI method

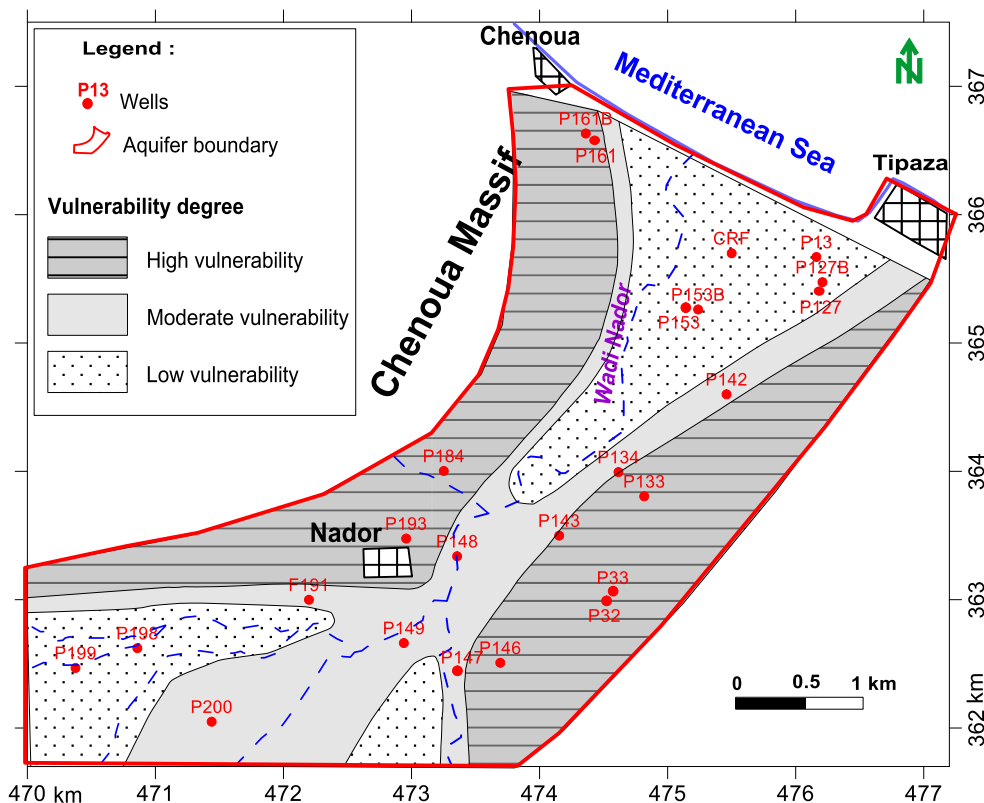


Table 7 Vulnerability class according to GALDIT index

Samples	G	A	L	D	I	T	GALDIT index	Vulnerability class
199	10	5	2.5	2.5	2.5	10	4.50	Low vulnerability
200	7.5	5	2.5	2.5	5	10	4.50	Low vulnerability
198	10	5	2.5	2.5	2.5	10	4.50	Low vulnerability
191	10	5	2.5	2.5	5	10	4.67	Low vulnerability
148	10	5	2.5	2.5	2.5	10	4.50	Low vulnerability
149	10	5	2.5	2.5	2.5	10	4.50	Low vulnerability
184	7.5	7.5	2.5	2.5	2.5	10	4.83	Low vulnerability
193	7.5	7.5	2.5	2.5	2.5	10	4.83	Low vulnerability
143	7.5	7.5	2.5	2.5	2.5	10	4.83	Low vulnerability
146	7.5	7.5	2.5	2.5	2.5	10	4.83	Low vulnerability
147	7.5	5	2.5	2.5	2.5	10	4.33	Low vulnerability
134	7.5	7.5	2.5	2.5	5	10	5.00	Low vulnerability
133	7.5	10	2.5	2.5	5	10	5.50	Moderate vulnerability
33	7.5	10	2.5	2.5	5	10	5.50	Moderate vulnerability
32	7.5	10	2.5	2.5	5	10	5.50	Moderate vulnerability
142	10	7.5	2.5	2.5	10	10	5.50	Moderate vulnerability
153	10	7.5	2.5	5	10	10	6.17	Moderate vulnerability
153B	10	7.5	2.5	5	10	10	6.17	Moderate vulnerability
127B	7.5	7.5	5	7.5	10	10	7.33	Moderate vulnerability
127	7.5	7.5	5	7.5	10	10	7.33	Moderate vulnerability
13	10	7.5	5	10	10	10	8.17	Moderate vulnerability
CRF	10	7.5	7.5	10	10	10	8.83	High vulnerability
161	10	10	10	10	10	10	10.00	High vulnerability
161B	10	10	10	10	10	10	10.00	High vulnerability

parameter is 10, whereas for unconfined aquifer is composed of sandstone and limestone, hence the rating value of 7.5 is attributed, according to the GALDIT model rating table (Table 3).

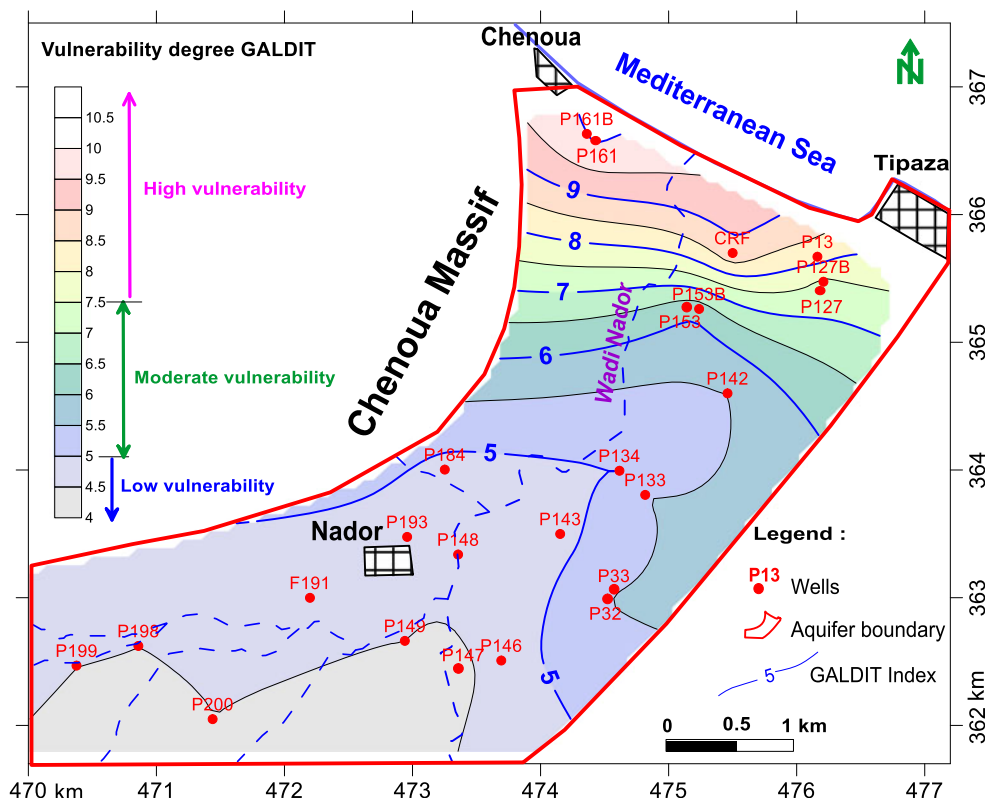
Parameter A Aquifer hydraulic conductivity is considered as a measure of the water movement rate (in the horizontal direction flow) through the saturated zone. The magnitude of seawater front movement is influenced by hydraulic conductivity (Lobo-Ferreira et al. 2005; Chachadi and Lobo-Ferreira 2001; Recinos et al. 2015). According to GALDIT index, parameter rating values range from 2.5 to 10 for minimum and maximum vulnerability impact, respectively, (Table 3). The study area has the following characteristics: (1) downstream zone a considerable hydraulic conductivity exceeding 4.6×10^{-4} m/s (>40 m/day), (2) central zone of a hydraulic conductivity ranging between 10^{-4} and 5×10^{-4} m/s, and (3) upstream zone of low values of a hydraulic conductivity 1.15×10^{-4} m/s (<10 m/day), which results in vulnerability ranging between 5 and 10 according to GALDIT classification.

Parameter L Height of groundwater level above sea level primarily refers to the piezometric conditions of the

investigated costal aquifer and is considered as a dynamic parameter, due to its temporal variation. Its importance for the hydraulic interpretation of the seawater intrusion mechanism can be realized from the theoretical approach of the so-called Ghyben-Herzberg principle (Recinos et al. 2015). GALDIT index ranges between 2.5 (minimum vulnerability impact) and 10 (maximum vulnerability impact). Seventy percent of the area has a piezometric level above 2 m above sea level (a.s.l) (vulnerability index of 2.5), while in the coastal zone, the groundwater level is below 2 m a.s.l (vulnerability index ranges between 5 and 10).

Parameter D Distance from the shore; the impact of seawater intrusion generally decreases as one move inland at right angles to the shore. The maximum impact is witnessed close to the coast. The parameter of distance to shoreline could then be calculated by measuring the distance from the different monitoring wells to the closest shoreline. The distance was classified by assigning GALDIT rating values according to Table 3 (Chachadi 2005), ranging from 2.5 (minimum vulnerability impact) to 10 (maximum vulnerability impact). Seventy percent of the wells are located at a distance more than 1000 m (vulnerability index of 2.5).

Fig. 3 Vulnerability to seawater intrusion using GALDIT method



Parameter I The impact of existing status of seawater intrusion is based on Cl^-/HCO_3^- ionic ratio. The data concerning the chloride and bicarbonate concentrations were obtained for different monitoring wells. This ionic ration was divided from the most affected area with vulnerability index of 10 (concern coastal aquifer, where the concentrations of chloride exceed 2000 mg/L), to the least affected area with vulnerability index of 2.5 (concern the recharge area in the upstream of plain, where the concentrations of chloride low than 250 mg/L).

Parameter T This parameter represents the thickness of the saturated zone, hence calculated since the difference between the groundwater table and the bottom of the aquifer. The aquifer thickness in the study area ranges from 20 to 60 m; therefore, the value of 10 (for high vulnerability impact) was assigned since the aquifer thickness in the area exceeds the 10 m (Chachadi 2005).

The final vulnerability map derived from the GALDIT index of this study area is shown in Fig. 3. The GALDIT vulnerability index ranges between 4.3 and 10, with three classes quite distinct (<5, 5–7.5, and >7.5) representing low, moderate, and high, respectively, covering areas of more than 50 % for moderate and high vulnerability characterization (mainly located in the center and coastal area) and the remaining area has low vulnerability characterization. The upstream area is considered to have a low vulnerability to degradation by seawater intrusion. The

moderate vulnerability is located in the center of the plain (vulnerability index ranges between 5 and 7.5), while the high vulnerability class is mainly located at the northern part of the area and extending approximately 3.5 km to the shoreline. It is evident that the fringe littoral areas in proximity to the Mediterranean Sea are more likely to be vulnerable to seawater intrusion than other areas; this is due also to the high hydraulic conductivity of aquifer (in

Table 8 The weight (w_i) and relative weight (W_i) of each chemical parameter

Parameter	WHO (2008) standard	Weight (w_i)	Relative weight (W_i)
EC	1500	5	0.135
pH	8.5	3	0.081
Cl	250	5	0.135
SO ₄	250	5	0.135
HCO ₃	250	1	0.027
Na	150	5	0.135
Ca	100	2	0.054
Mg	50	5	0.135
NO ₃	50	5	0.135
K	12	1	0.027

$\sum_{i=1}^n w_i = 37$

Table 9 Calculation of WQI for individual water samples

Sample	WQI	Classification
P199	87.91	Good water
P200	112.56	Poor water
P198	99.54	Good water
F191	100.73	Poor water
P148	87.09	Good water
P149	86.53	Good water
P184	116.13	Poor water
P193	110.16	Poor water
P143	111.13	Poor water
P146	106.90	Poor water
P147	103.05	Poor water
P134	142.69	Poor water
P133	130.65	Poor water
P33	112.78	Poor water
P32	109.01	Poor water
P142	218.56	Very poor water
P153	371.53	Water unsuitable for drinking purpose
P153B	373.07	Water unsuitable for drinking purpose
P127B	258.68	Very poor water
P127	265.41	Very poor water
P13	303.26	Water unsuitable for drinking purpose
CRF	388.33	Water unsuitable for drinking purpose
P161	481.18	Water unsuitable for drinking purpose
P161B	481.25	Water unsuitable for drinking purpose

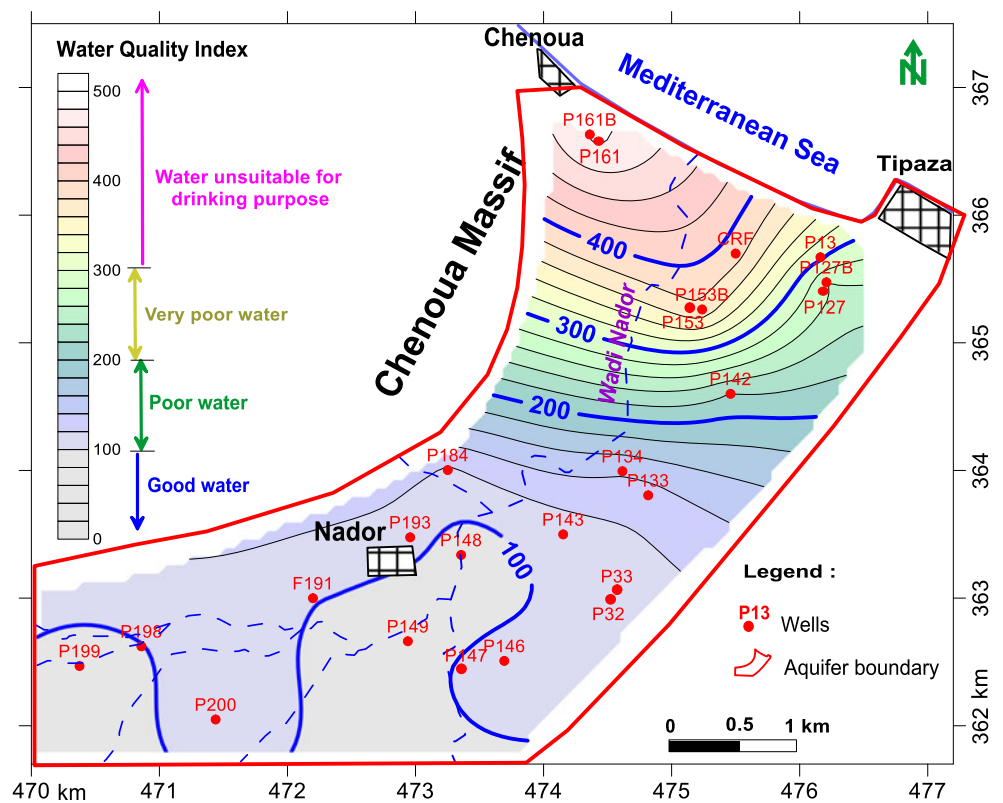
order to 6.8×10^{-4} m/s) and also to the groundwater pumping.

Evaluation of groundwater quality

In the study area, the assessment of groundwater quality was carried out to identify its suitability to drinking purpose by the estimation of water quality index for drinking purposes. WQI is an important parameter for demarcating groundwater quality and its suitability for drinking purposes (Mishra and Patel 2001; Naik and Purohit 2001; Avvannavar and Shrihari 2008). Calculation of WQI for each sample is represented in Table 8. During dry period of 2013, 16.67 % of groundwater samples represent “good water,” 45.83 % indicate “poor water,” 12.5 % indicate “very poor water,” and 25.0 % show “water unsuitable for drinking purpose.”

It is obvious from this classification that groundwater from the study area is not of excellent quality for drinking, but the majority of wells are characterized by poor or very poor quality (Table 9). The spatial distribution map of WQI indicates that the coastal area has very poor groundwater quality and groundwater that is unsuitable for drinking purpose. This may be due to effective leaching of ions, effect of seawater intrusion, direct discharge of urban reject (infiltration of pollutants present at the surface), and agricultural impact (agricultural fertilizers).

Fig. 4 WQI map of Nador aquifer during dry period of 2013



In general, the groundwater quality decreases from the south to the north of the Nador aquifer. It is related to the high values of chloride, sodium, sulphates, nitrate, and magnesium (Fig. 4).

Conclusions

The groundwater of Nador plain has been intensively exploited during the last two decades, to ensure the demands of intensive agricultural activities and at the same time, the supply of drinking water. As a result, the quality of the groundwater has been deteriorated due to seawater intrusion and other contaminant processes such as chemical fertilizers used in the agricultural activities and urban wastewaters.

In this work, the AVI and GALDIT methods were employed to determine the groundwater vulnerability to contamination from anthropogenic activities and seawater intrusion in Nador coastal aquifer. The groundwater quality has been also evaluated based on the water quality index for assessing groundwater for drinking purposes.

Using AVI method, more than 80 % of the total surface of the Nador aquifer presents moderate to high vulnerability, which makes it susceptible to pollution and degradation by superficial sources of contamination. In fact, areas where the outcrops of the aquifer are observed show a high vulnerability to the anthropogenic pollution. It is due to the high hydraulic conductivity of unsaturated zone, where the contaminants attain rapidly the water table. The highest degrees of vulnerability, obtained with the AVI method, corresponding to zones of anthropogenic pressure, are highest with the presence of agricultural activities, urban discharge of rural agglomeration, landfill, and roads, all of which increase the risk of contamination.

The GALDIT method shows that the coastal part of the aquifer is highly susceptible to seawater intrusion, which is coherent with the characteristics of the aquifer. The vulnerability potential to seawater intrusion was assessed taking into consideration various influencing factors such as groundwater occurrence, hydraulic conductivity of the aquifer, thickness of the aquifer, the groundwater level under mean sea level, the distance from the shore, and the exploitation of groundwater. According to GALDIT method, the aquifer is highly vulnerable up to 2 km inside the plain.

The WQI results show that groundwater quality for drinking purposes decreases from upstream to downstream of the study area. This is mainly due to the flow direction moving from south to north, the effect of seawater intrusion and to other contaminant processes. The WQI shows a higher value in coastal sector, indicating a deteriorated groundwater quality; it is unsuitable for drinking purposes.

This study demonstrates that the use of vulnerability methods and WQI method could provide useful information for groundwater vulnerability and quality assessment in coastal aquifers. Consequently, AVI, GALDIT, and WQI are efficient tools to summarize and to report on the monitoring data to the decision-makers in order to minimize groundwater contamination by seawater intrusion and anthropogenic activities and to be able to understand the status of the groundwater quality.

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