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ORIGINAL PAPER

Assessment of aquifer vulnerability using a geophysical approach in hyper-arid zones. A case study (In Salah region, Algeria)

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Abstract Assessment of aquifer vulnerability to contamination is an effective tool for the delineation of groundwater protection zones. Geophysical approach was used to determine vulnerability zones in a study area located at 70 km north part of In Salah region, Southern limits of hydrogeological occidental basin in the outcrops Continental Intercalaire terrains. Ninety vertical electrical soundings (VES) were conducted in the study area. The results from the electrical survey data were used to assess the potential risk of groundwater pollution and define the protective properties of geologic layers as well as identifying suitable areas with poor, moderate, and high aquifer protective capacity rating. The inverted resistivity values and thickness of the layers above the groundwater table were used in order to estimate the integrated electrical conductivity (IEC) that can be also used for the quantification of aquifer vulnerability.

Keywords Aquifer vulnerability · Groundwater protection · Thickness of the layers · Apparent resistivity · Integrated electrical conductivity

Introduction

Groundwater is an essential commodity for the well-being of human societies to live in arid and hyper-arid areas. The quality of groundwater plays an important role in the water scarcity regions, especially for drinking water supply (Al Hallaq 2002). During the recent decades, the groundwater exploitation has dramatically increased and hence the agricultural use of water has grown rapidly, while the increasing concentration of populations in urban areas has meant that large-scale well fields have been developed for urban water supply. These situations make the groundwater more easily vulnerable to pollution. Furthermore, vulnerability is the degree to which human or environmental systems are likely to experience harm due to perturbation or stress and can be identified for a specified system, hazard, or group of hazards (Popescu et al. 2008). In hydrogeology, vulnerability assessments typically describe the susceptibility of the water table, a particular aquifer, or water well to contaminants that can degradate the groundwater quality (e.g., nitrates, industrial chemicals, and hydrocarbons). The contaminants may originate from a natural source (e.g., rock containing arsenic) or be introduced by human activity (e.g., agriculture:fertilizers; industry:chemical storage and spills) (Liggett and Talwar 2009). Vulnerability assessments are also powerful educational tools for raising public awareness of groundwater protection issues, which is an on-going need (Nowlan 2005). The intensive utilization of aquifers has changed the groundwater chemical quality. According to Foster et al. (2002), contamination of groundwater occurs when the load of contaminants on the ground or leachates generated by urban, industrial, agricultural, or mining activities is not adequately controlled, and certain components exceed the natural attenuation capacity of subsoil and cover layers. The study of these changes requires the design of monitoring networks. One of the most successful tools for

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further investigation, protection, and monitoring system has been the use of vulnerability maps. Vulnerability maps have become an ever more essential tool for groundwater protection and environmental management (Vias et al. 2005). The studies on vulnerability are mostly based on the development of vulnerability maps using index (and overlay) methods, because they are easy to implement, inexpensive to produce, use readily available data, and often produce categorical results (Focazio et al. 2002). Among the methods used to evaluate the aquifer vulnerability, DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stempvoort et al. 1992), SINTACS (Civita 1994), ISIS (Civita and De Regibus 1995), GLA (Hölting et al. 1995), DAC (Celico 1996), HYDROmed (Ketelaere et al. 1997), U.K. vulnerability system (Palmer and Lewis 1998), EPIK (Doerfliger et al. 1999), IRISH (Daly and Drew 1999), PI (Goldscheider et al. 2000), VURAAS (Cichocki and Zojer 2007), and COP (Vias et al. 2006) are purely analytical hydrogeologic assessments.

However, several studies have use the resistivity methods for the quantification of aquifer vulnerability, as Kalinski et al. (1993a, b); Rottger et al. (2005); Lenkey et al. (2005), Casas et al. (2008), Abiola et al. (2009); Atakpo and Ayolabi (2009), and Omosuyi (2010). A simple method for assessment and quantification of aquifer vulnerability based on the electrical conductivity has been proposed. Christensen et al. (2002) successfully tested the method for the Flensburg area (Danish-German border region). This method is called Integrated Electrical Conductivity, IEC (Rottger et al. 2005).

In the present study, a sector of the Continental Aquifer system has been chosen in order to test and apply the electrical conductivity in the assessment of groundwater vulnerability. Thus, the main objectives of the study are to carry out detailed geological and hydrogeological mapping of the study area and to conduct geophysical approach to assess the aquifer vulnerability.

The study area

The study area is located in the north part of In Salah region (Southeast of Algeria; Fig. 1). This region is defined by latitude 27° 11′ N and longitude 2° 28′ E covering an area of 43, 937.50 km^2. It occupies about 7.88 % from Tamanrasset Province, which extends over a Reg, represented by a small slope ranges from 1 to 2 %. The heterometric deposits covered at elevations that vary from 350 to 450 m. Its natural boundaries are the Tademaït plateau to the north, the sand dunes, locally represented by Mahabes Tiguendaft Erg, which butts farther on the northern prolongation of Tademaït plateau to the West. The straightening Paleozoic bedrock ensures the closure of hydrological system to the east, and finally depression closed by endorheic character, which encompasses sebkha and palm trees to the South.

In Salah region has a hyper-arid to arid climate with low and scarce rainfall. Average annual rainfall is about 19 mm. In addition, the temperature is moderately high throughout the year, with an annual range from 20.5 to 45 °C and a potential evaporation rate of 4120 mm/year, with the hottest period of the year during the dry season. These conditions assuring the persistence a steppe vegetation type. The hydrographic system is constituted by ephemeral rivers; the most important are Souf, Rokna, and Redjem. The latter are supplied in an intermittent way by local rainfall. Increases of the industrial, domestic effluents and intensive pumping have largely contributed to the contamination of groundwater.

The geological setting of In Salah region is the southern limits of Occidental basin of the North Sahara Aquifer System (NSAS) in the outcrops Continental Intercalaire (CI) (Fig. 2). According to Kilian (1932), the term "Continental Intercalary" means a continental episode located between the two marine sedimentation cycles: the Paleozoic cycle, which completes the hercyian orogenesis at the bottom, and the upper Cretaceous cycle, from the Cenomanien transgression at the summit. The Continental Intercalaire formation is represented by sandy-sandstone and sandy clay of the Lower Cretaceous continental deposits (Cornet 1964), unconformably overlain a clastic formation ranging from Cambro-Ordovician to Carboniferous essentially comprising sand, sandstone (conglomerate on the bottom of Cambrian) with intercalations of marl, clay and some limestone beds (Busson 1967).

The hydrogeological cross-section along the region is presented in Fig. 3. It shows the presence of a horizontal structure composed by the coarse gravel siliceous sand fine to medium, red sandstone tender crossing sandy red clay of Lower Cretaceous age; it total thickness is of 300 to 400 m (UNESCO 1972). This latter is limited to the bottom by red clay compact and sandstone, representing the aquifer basement. On the top, heterogeneous coarse materials represented essentially by Quaternary (alluvium).

The aquifer is recharged by two different ways. First, is a direct infiltration of rainfall and runoff, which are occurred on outcrop areas on the West (Touat-Gourara) and on the South (Tidikelt) of Tademaït Plateau; secondly, is an indirectly in Grand Erg Occidental across dune sands and Continental Terminal Terrains (ERESS 1972; BRL 1998; and OSS 2003).

The groundwater flow directions are generally north towards the south, from the Saharan Atlas piedmont to the Grand Erg Occidental, Touat-Gourara and Tidikelt (UNESCO 1972; Guendouz 1985; Mamou 1990; Edmunds and Gaye 1997; Edmunds et al. 2003); natural outlet is formed by borders West and South of Tademaït where are located the *foggaras* of Gourara, Touat and Tidikelt (OSS 2003).

Finally, this region is characterized by the oases formerly supplied via foggaras and artesian wells, since the early twentieth century, but this artesianism has been decreasing during the current years, due to over-exploitation of water resources.

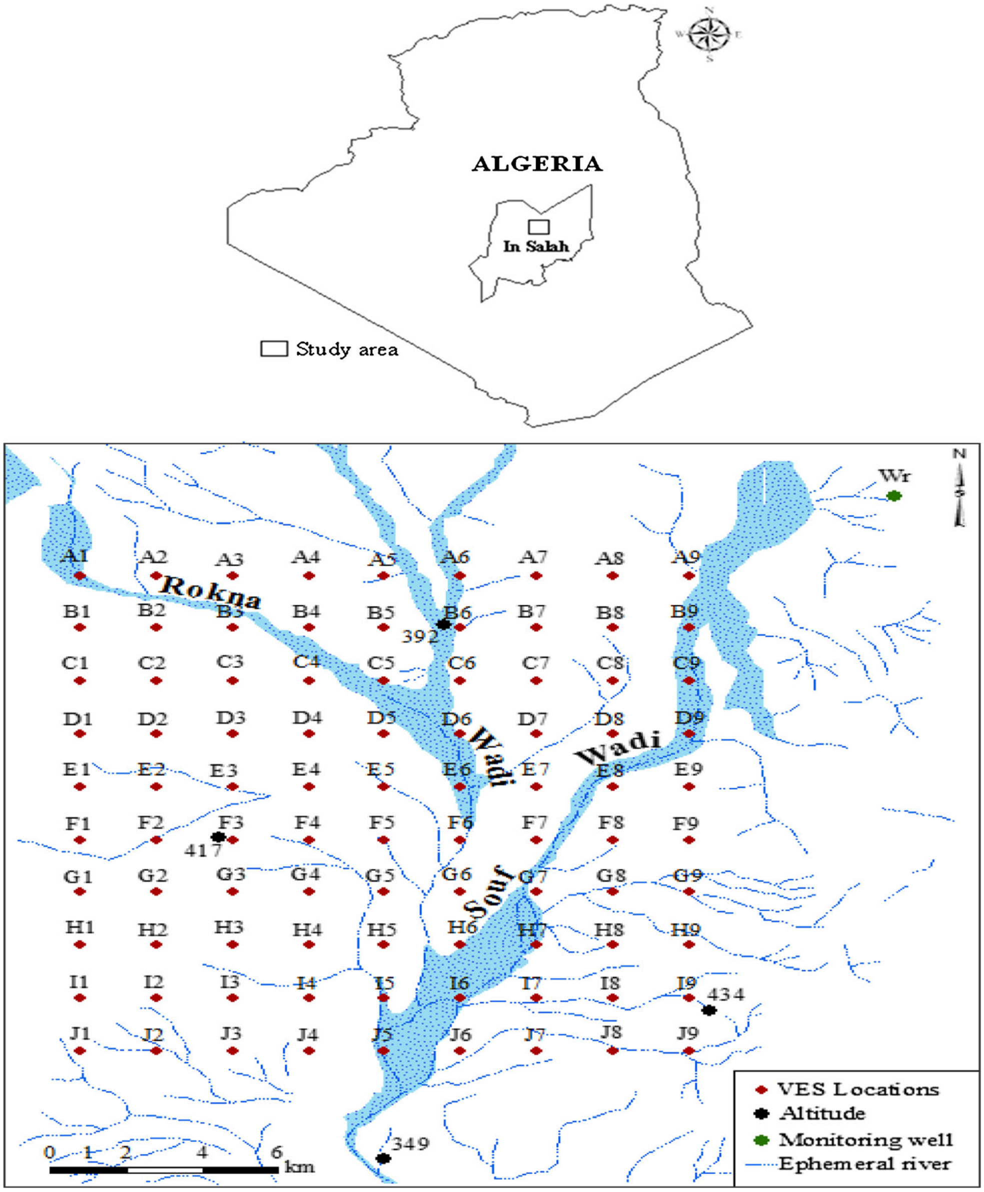


Fig. 1 Location map of study area and VES positions

The exploitation, during the period of 1902–2012, is marked by an important increase in time. The quantity of water resources exploited increased from 0.25 m^3/h in 1902 to 60 m^3/h in 2012, according to the data of National Hydraulic Resources Agency (ANRH, its French acronym). This situation is reflected also by the increasing drawdown and degradation of water quality in some areas that are more vulnerable to salinization.

Material and Methods

Electrical resistivity method

Vertical electrical sounding (VES) survey was carried out at 90 points using Schlumberger four-electrode configuration. These sounding points were measured by the engineering office BEREGH (2008, Etude géophysique par prospection électrique de la zone N°1 Oued Souf dans la region d'In Salah, unpublished) and used to identify the nature and the extension of the aquifer within the study area. The VES points are located on a level with Souf Wadi (Fig. 1), numbered A–J, and marked as A1–J9 were established covering an area of 288 km^2. The sounding points spacing was 2 km while the maximum value of emission line AB chosen was 4000 m, which allowed a vertical investigation reaching up to 600 m in depth. The electrode spread of AB/2 was varied from one to a maximum of 2000 m. The expected depth of investigation was ranging between $L/5$ and $L/3$, where $L = AB/2$ and AB the current electrode. The apparent resistivity values of the layers were measured using the resistivity meter in association with the generator system reaches up to 6000 m in depth.

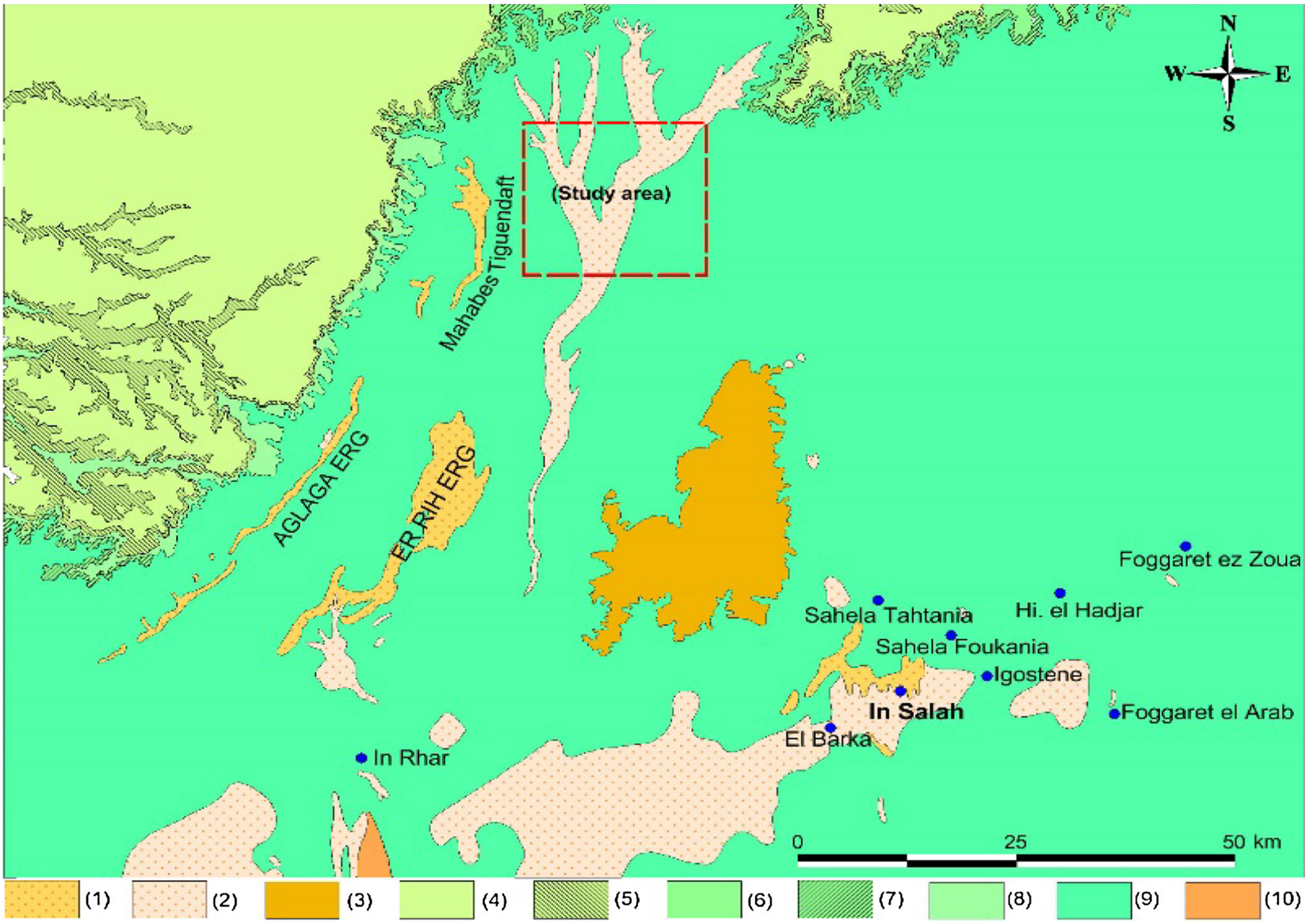


Fig. 2 Geologic map of In Salah showing the study area. (*1*) Dunes, (*2*) recent quaternary: clayey sand alluvium, (*3*) tertiary continental: clay and sandstone, (*4*) upper Senonian: limestone, (*5*) lower Senonian: clay gypsum, (*6*) Turonian: dolomite and chalk, (*7*) Cenomanian: dolomite, (*8*) Cenomanian and Turonian: dolomite and clay, (*9*) Lower Cretaceous: clay, sandstone, gravel, and sand, (*10*) Lower Visean Carboniferous: clay

Field resistivity structures of sounding data were interpreted quantitatively by computer iteration with the aid of the software IPI2Win (version 2.1) developed by the Geophysics Group Moscow State University for inverse interpretation to obtain the true resistivity and thickness of the layers. The software was further used for both computer iteration and modeling. Computer iteration was carried out to reduce errors to a desired limit and to improve the goodness of fit. The fit between model response and the field data for the VES points were generally lower than 8 %.

Geoelectrical methods are used to obtain the following physical parameters of geological formation (Komatina 1994) and determine the flow of electric current in the formation (Sundararajan et al. 2012). Resistivity varies with the texture of the rock, nature of mineralization, and conductivity of electrolyte contained within the rock (Parkhomenko 1967). Resistivity not only changes from formation to formation but also changes within a particular formation (Sharma 1997). Resistivity increases with grain size and tends to maximum when the grains are coarse (Sharma and Rao 1962), also when

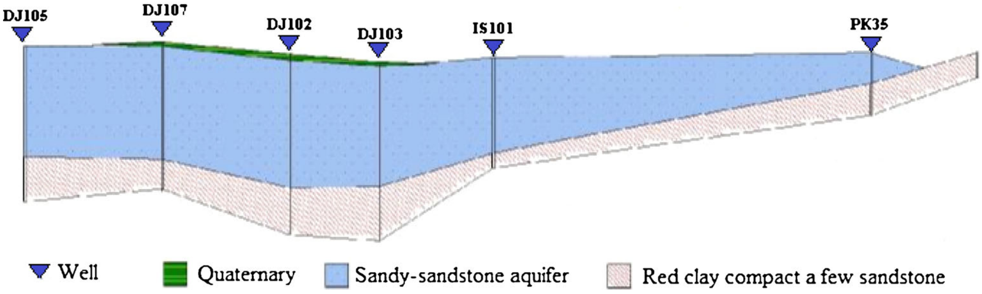


Fig. 3 Hydrogeological cross-section of study area (modified from ANRH-DRSO 2004)

the rock is fine grained and compact such as dolerite dyke (Sankaran et al. 2010).

The spatial distribution of electrical parameters of the subsurface can provide valuable information for characterizing the heterogeneity of the groundwater and the soil zone. The geoelectrical method is an effective tool for ascertaining the subsurface geological framework of an area (Griffith and King 1965; Keller and Frischknecht 1966; Zohdy et al. 1974; Griffith 1976; Kelly 1977; Zohdy 1989). However, it becomes an increasingly important tool in subsurface hydrogeological applications (Kirsch 2006). Geoelectrical measurements can contribute to the determination of catchment areas and aquifer characteristics, such as hydraulic conductivity, sorption capacity, dominant flow regime (Worthington 1975; Allessandrello and Lemoine 1983; Mazac et al. 1990; Boerner et al. 1996; Kemna 2000; Soupios et al. 2007; Sinha et al. 2009; Tizro et al. 2010; Massoud et al. 2010; Weihnacht and Boerner 2005), the monitoring of water content, water movement and water quality (Daily et al. 1992; Gruhne 1999; Berger et al. 2001; Berthold et al. 2004; Liu and Yeh 2004; Mhamdi et al. 2006; Boughriba et al. 2006; Al-ahmadi and El-Fiky 2009), evaluation the protection of groundwater resources (Henriet 1975; Douma et al. 1990; Robert et al. 1993; Braga et al. 2006) and mineral alteration connected with active remedial measures on contaminated sites as well as with natural attenuation processes (Grissemann et al. 2000; Atekwana et al. 2004), the assessment of aquifer vulnerability and depth to water table (Kalinski et al. 1993a; Kirsch 2000). Geoelectrical methods are used extensively in groundwater mapping for the investigation of the vulnerability of aquifers and shallow aquifers themselves (Kirsch et al. 2006). The clay content of the formation defines the electrical formation resistivity with clayish less permeable formations showing low resistivities and sandy permeable formations showing high resistivity values. The geoelectrical method is capable of mapping both low and high resistive formations and therefore a valuable tool for vulnerability studies (Christensen and Sorensen 1998; Sorensen Kurt et al. 2005).

The main relationship between the electrical conductivity and vulnerability of aquifer based on the key principal called the clay content of the material. The clay content related to hydraulic conductivities of soils (Scheffer and Schachtschabel 1984) and influences on the electrical resistivity or conductivity. High clay content generally corresponds with low resistivities and low hydraulic conductivities, increasing clay content leads to decreasing electrical resistivity or to increasing electrical conductivity (Sen et al. 1988). Of special interest for vulnerability assessment is the groundwater covering layers above the water table, the unsaturated zone.

Assessment of aquifer vulnerability

The key expression for a quantification of aquifer protection is vulnerability. Vulnerability of an aquifer 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 1999). It is defined by the characteristics of the covering layers, which are called protective layers (Kirsch 2006). Younger (2007) define aquifer vulnerability as the readiness with which a given aquifer is likely to become polluted. The vulnerability of a certain area can be described by the degree of susceptibility of that area to groundwater pollution (Baalousha 2006). In 1968, the French Margat was the first who used the term vulnerability in hydrogeology; thereafter, the concept was adopted worldwide (Albinet and Margat 1970; Haertle 1983; Aller et al. 1987; Foster and Hirata 1988; Adams and Foster 1992; Drew and Hötzl 1999; Zwahlen 2003). Recently, several propositions have been given by scientists to define the groundwater vulnerability, many are quite similar; however, there is not any recognized and accepted common definition that has been developed yet. The concept of vulnerability assessment used in this case is similar to concepts of the Aquifer Vulnerability Index (AVI) and is a widely used method to assess the aquifer vulnerability to surface contaminants (Van Stempvoort et al. 1992). This method quantifies groundwater vulnerability by hydraulic resistance to vertical flow of wastewater through the unsaturated layers. The hydraulic resistance (C) can be obtained using the formula:

$$C=\sum\nolimits_{i=1}^{n}\frac{h_i}{k_i} \tag{1}$$

where k_i and h_i are, respectively, the hydraulic conductivity and the thickness of the layers above the aquifer zone. Alternatively, the state geological surveys (SGD) a vulnerability quantification system based on the cation exchange capacity (CEC) of the protective layers (Hölting et al. 1995). Vulnerability is quantified by a protection function S_G (Schutzfunktion) calculated by:

$$C=\sum\nolimits_{i=1}^{n}d_i.G_{Li} \tag{2}$$

where d_i and G_{Li} are thickness and cation exchange capacity code (Punktzahl) of each covering layer: as the electrical conductivity is related linear to the cation exchange capacity (G_{Li}) and the hydraulic conductivity (k_i) can be replaced by the electrical conductivity (σ_i) or the resistivity (ρ_i) to calculate the hydraulic resistance (C) which is called Integrated Electrical Conductivity, IEC (Rottger et al. 2005) or a Geophysical Based Protection Index, GPI (Casas et al. 2008). The IEC can be used to assess the aquifer vulnerability by:

$$IEC=\sum\nolimits_{i=1}^{n}h_i.\frac{1}{\rho_i} \tag{3}$$

Then, function (3) can be rewritten as:

$$IEC=\sum\nolimits_{i=1}^{n}h_i.\sigma_i \tag{4}$$

Where

$$\sigma_i = \frac{1}{\rho_i} \tag{5}$$

The resistivity (ρ_i) and thickness (h_i) of each layer above the aquifer are obtained from the inversion of resistivity sounding. The estimated IEC unit is ohm^{-1} (Ω^{-1}) or Siemens (*S*). In our studied area, vulnerability index or integrated conductivity is calculated for all layers above the groundwater table. Depth to water is one of the most important natural factors because it determines the thickness of material through which infiltrating water must travel before reaching the saturated zone. Rottger et al. (2005) suggested two options to set the depth level: a fixed distance in relation to ground surface or a fixed depth related to sea level. In this case, a fixed distance to the ground surface is recommended to show the protection of deep aquifer. Thus, the aquifer potential protection increases with depth to water. In other words, the water table is the first occurrence of groundwater. Above the water table is the unsaturated zone, usually regarded as key factor determining the vulnerability of an aquifer system (Thomas and Leah 2001) and the first line of defense against pollution, which describe conditions of the unsaturated zone that is often found to be the most important single parameter (McLay et al. 2001; Herbst et al. 2005).

The unsaturated zone is very important in protecting the underlying groundwater, especially where soils are thin and/or poorly developed. An aquifer can be classified as well protected if the percolation time through the unsaturated covering layers exceeds 10 years (Hölting et al. 1995). The character of the unsaturated zone and its potential attenuation capacity then determine the degree of groundwater vulnerability (Migdad 2011).

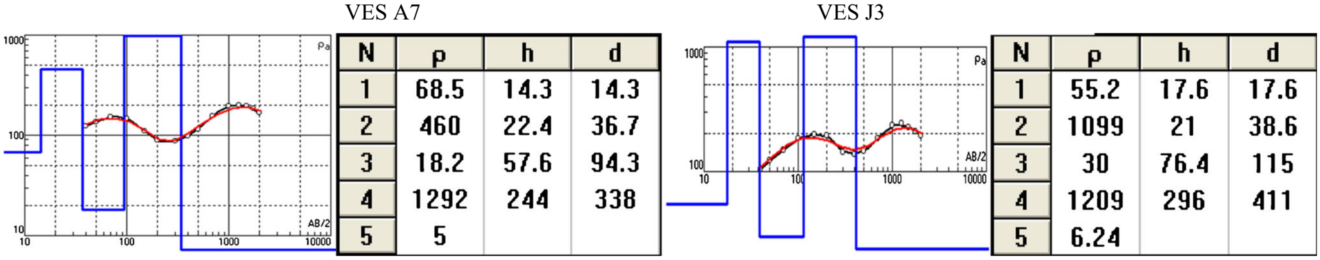
Although in the literature vulnerability assessment is mainly restricted to the unsaturated layers above the first groundwater horizon, for deeper aquifers like Continental Intercalaire aquifer the entire sequence of covering layers should be taken into account, if detailed underground information are available. The main unsaturated zone properties that are important in vulnerability assessment are the thickness, lithology variations which determine the inaccessibility of the underlying aquifer units (Wilson 1983) and vertical hydraulic conductivity of the materials. The thickness depends on the depth to the water table, which can vary significantly due to local topography and fluctuates seasonally, and both these have to be taken into account when determining thickness. Lithology of the vadose zone controls infiltrability and other various physicochemical processes (Robins et al. 2007; Zhou et al. 2010). Besides, the vertical hydraulic conductivity of unsaturated zone and its structure are directly influence the transfer time of a contaminant until reaches the water table.

Results and discussions

The quantitative treatment of the VES provided geoelectrical information characterized by the values of resistivity and thickness (layer parameters) of the various geoelectrical layers. The layer parameters derived from the graphical curves obtained are shown in Fig. 4 (VES A7 and J3). The curves of electrical soundings allowed us to distinguish the succession of layers informing about the heterogeneity of the terrain.

In order to correlate the geophysical surveys with the geology of the study area, geological data were collected from the surface and subsurface, and electric surveys of calibration were developed close to the monitoring well (Fig. 5). The geoelectrical model was determined as a function of the calibration with the data from well and the resistivity contrast between high and low values.

Typical forms of these curves are KHK, QHK, HAK, HKQ, AKQ, and KQQ types. Most of sounding curves obtained were of the KHK-type ($\rho_1 < \rho_2 > \rho_3 < \rho_4 > \rho_5$), i.e., a flattened appearance, highlighting a succession of area relatively conductive and resistant to very resistant. Calibration of electrical survey supported by a detailed analysis of the results on the study area correlated with lithologic description logs we can set the following resistivity scale presented in Table 1. Examination of this scale can be defined the following sequence of layers with contrasted resistivities: A layer of resistivity different they have the same age of formation: sandy clay (30–90 Ωm) and (15–50 Ωm), clayey sand (100–380 Ωm) and (50–120 Ωm) of Lower Cretaceous, clay sandstone (5–52 Ωm) of Paleozoic. In addition, the resistivity of the



VES A7

N	ρ	h	d
1	68.5	14.3	14.3
2	460	22.4	36.7
3	18.2	57.6	94.3
4	1292	244	338
5	5		

VES J3

N	ρ	h	d
1	55.2	17.6	17.6
2	1099	21	38.6
3	30	76.4	115
4	1209	296	411
5	6.24		

Fig. 4 Typical VES curve and model description. ρ_i in Ωm, *h* and *d* in m

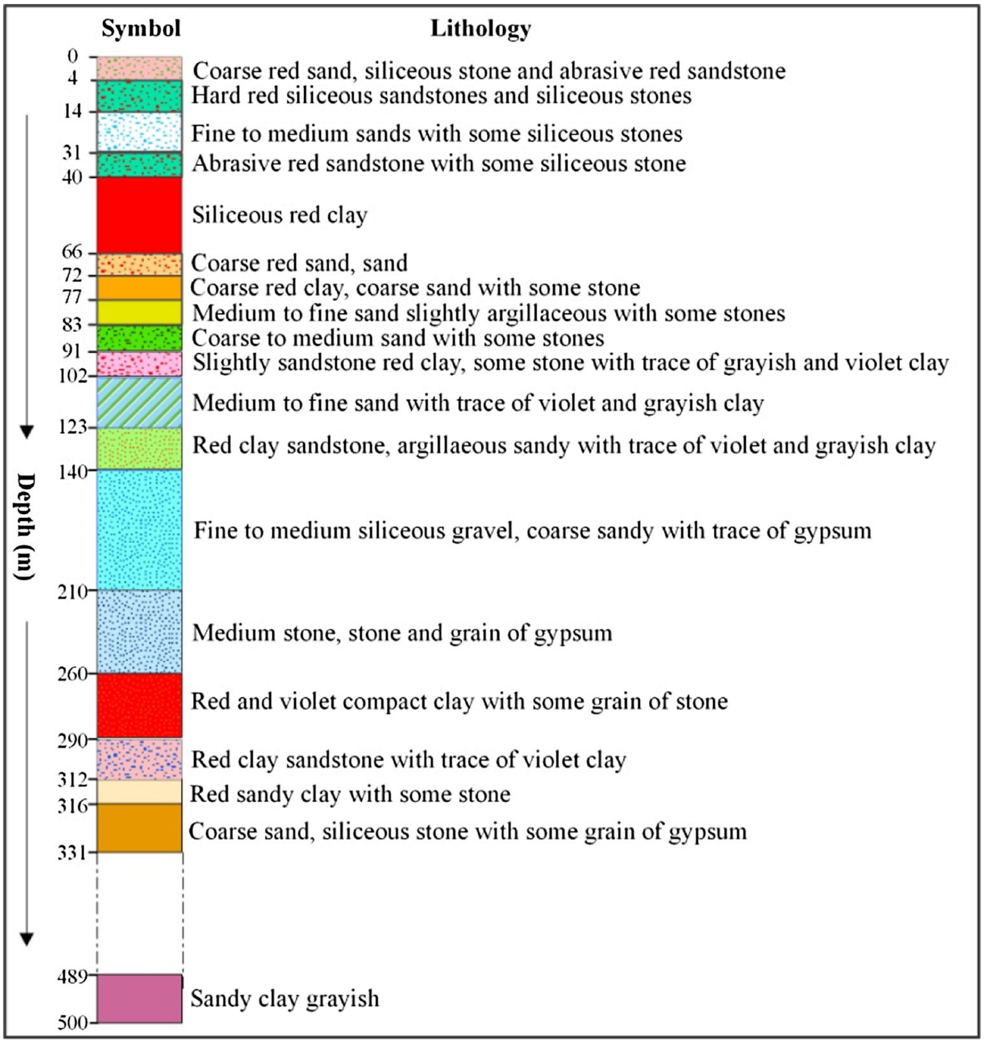


Fig. 5 Lithology of monitoring well

sandstone formation has a very broad range of variation (270–2400 Ωm) and (410–4800 Ωm), due to variations of the particle size of material, state of water saturation, degree of consolidation, nature of the cement (siliceous or carbonate), and chemistry of the water imbibitions.

Depth to water table is a significant parameter of the IEC controlling the ability of contaminants to reach the groundwater or aquifer. The groundwater table is clearly defined by resistivity values ranging from 15 to 120 Ωm. Covered with sandstone formation, the resistivity contrast is 270–2400 Ωm/15–120 Ωm. The electrical conductivity values in the saturated zone are much higher than the values in the unsaturated zone (Rottger et al. 2005). Unsaturated zone can be defined as that zone above the water table, which is discontinuously saturated, lying between soil layer and water table (Kabera and Zhaohui 2008). The vadose zone influences aquifer potential contamination; it is essentially similar to that of

Table 1 Scale of local resistivity

Formation	Lithology	Resistivity (Ωm)
Lower Cretaceous	Sandy clay, sandstone and clayey sand	30–90
	Sandstone, slightly clayey sand	100–380
	hard sandstone, sandstone and partially saturated sand	270–2400
	Hard sandstone, siliceous sandstone	410–4800
	Sandstone and clayey sand	50–120
	Clay, Sandy clay	15–50
Paleozoic	Clay and clay sandstone	5–50

Table 2 Criteria of assessment the vulnerability with IEC method

Degree of vulnerability	Vulnerability index (*mS*)
Extremely High	<500
High	500–1000
Moderate	1000–2000
Low	2000–4000
Extremely low	>4000

Table 3 Summary statistics of IEC index

	Minimum	Maximum	Average	Standard deviation
IEC Index (*mS*)	222.42	5906.58	1737.33	985.98

Table 4 Criteria of quantification the percolation time with vulnerability index

Vulnerability index (*mS*)	percolation time
<500	Several months
500–1000	Several months—3 years
1000–2000	3–10 years
2000–4000	10–25 years
>4000	>25 years

aquifer media, depending on its permeability and on the attenuation characteristics of the media (Added and Hamza 2000). If vadose zone is highly permeable, then this leads to a high vulnerable (Corwin et al. 1997). The vadose zone has been identified from available geological map and hydrogeological cross-sections of the study area. The vadose zone is composed of heterogeneous coarse materials presented essentially by alluvium.

The concept of vulnerability assessment with IEC method is similar to concepts of AVI method (Van Stempvoort et al. 1992) or SGD method (Hölting et al. 1995): as the electrical conductivity is related linear to the cation exchange capacity, the cation exchange capacity is replaced by the electrical conductivity to form an integrated electrical conductivity IEC (Kirsch et al. 2003). Therefore, the close relation of IEC and SGD method attempts to use the criteria of vulnerability assessment by the SGD method to assess the vulnerability by IEC method (Table 2).

According to the IEC index, the aquifer vulnerability ranges from 220 to 6000 mS (Table 3), the values were categorized into five classes. They are extremely low (>4000), low (2000–4000), moderate (1000–2000), high (500–1000), and extremely high (<500) groundwater vulnerability.

A vulnerability map is shown (Fig. 6) in which the electrical conductivity index is calculated down to a depth of 102 m below the surface. As the groundwater level is high, the concept of the electrical conductivity index for the saturated zone was extended. The electrical conductivity values in the saturated zone are much higher than the values in the unsaturated zone. As the conductivity of the saturated zone is high, the influence on the electrical conductivity index is also low. If one assumes an earth model consisting of 14 m of sandstone and clayey sands (54 Ωm = 18.52 mS/m), 14 m of unsaturated sandstone and clayey sands (76 Ωm = 13.16 mS/m), the electrical conductivity index is calculated of 259.26 mS compared to an electrical conductivity index of 184.21 mS for the case of 14 m of unsaturated sandstone and clayey sands.

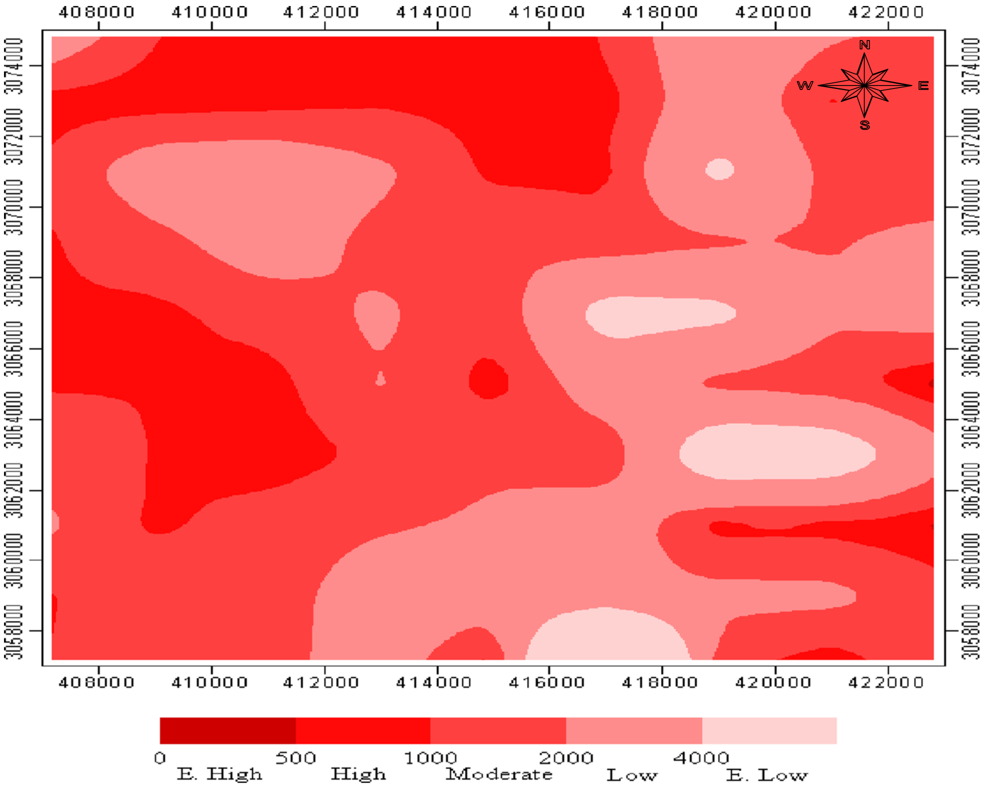


Fig. 6 Vulnerability map based on integrated electrical conductivity

Here, the class of extremely high vulnerability does not exist in our study area. In general, the vulnerability map would show not only the reflection of geological conditions but also the influence of topography in the study area. The obtained IEC value will have a maximum value when the thickness low resistivity above the aquifer is increased. The extremely low degree of vulnerability can be observed mainly at the central and the south parts, where the connection between the land-surface and the water table is consisted by clay sandstone. The low degree of vulnerability can be noticed at the central part, which is protected by sandstone, siliceous sandstones, and sandy clays. The moderate degree of vulnerability can be observed almost the study area, where the frequent lithology of unsaturated zone is mainly sandstones. The high degree of vulnerability is dominant at the west, northern, and southern parts of the study area, which the unsaturated zone is constituted by sandy clay, sandstone, and sand partially saturated. A vulnerability map is presented based on geophysical results. To quantify the vulnerability of the aquifer, the geoelectrical measurements can give an overview of the groundwater protection of the area (Kirsch 2009). Instance, Hölting et al. (1995) used the results of the airborne EM survey, for the calculation of protection index a depth of 30 m below the surface. More recently, Christensen et al. (2002) used the same principle in the area near to the city of Flensburg, for the calculation of the integrated conductivity. Moraine areas with high IEC and good aquifer protection can clearly be discriminated from sandy outwash plains with low IEC and poor aquifer protection. However, the realization of the vulnerability map by the IEC-method necessitates the use of two parameters which reliability depends on the quality of data used. One of difficulties of applying method of IEC is also the class limits, which are therefore not absolute values, but rather relative values. These limits can then vary from study to another study and from one region to another. As noted before, the extension of the electrical conductivity index for the saturated zone can also be controlled by percolation time of surface water.

For example, vulnerability maps for The Netherlands show the lateral distribution of depth to groundwater table, clay content, cation exchange capacity, and percolation time of surface water (RIVM 1987). Kalinski et al. (1993a) used the electrical conductivity to estimate the time of travel for percolating surface water. It must also be noted that the vertical travel time of surface water in the upper unsaturated layers can be related to the resistivity properties, which are based on the geological materials and thickness of protective layers. Kalinski et al. (1993a) and Rottger et al. (2005) have discussed this issue in detail. Kirsch (2009) suggested using vulnerability index to quantify percolation time (Table 4).

The moderate degree of vulnerability is dominant in this area, it can be seen that the range of percolation time is between 3 and 10 years (see Table 4). Hölting et al. (1995) classified an aquifer as well protected if the percolation time through the unsaturated covering layers exceeds 10 years.

Conclusions

Vulnerability assessment based on hydraulic conductivity can be backed by measured electrical conductivities. In a first approach, the vulnerability map based on the electrical conductivity have to make some assumptions about the distribution of different degree of vulnerability. While the most dominant class is the moderate class, then the electrical calibration curves identified resistivity intervals true characteristics for each type of surficial encountered. The sandy inclusions in clayey environment increased the aquifer vulnerability.

The concept of vulnerability is originally restricted to the unsaturated zone covering the first groundwater layer. However, as our main interest is to the deeper groundwater layers actually in use for water supply, the concept of vulnerability is extended to the saturated zone. The top of the groundwater layer used for water supply then gives the reference depth for the calculation of the electrical conductivity index.

A correction applied to the electrical conductivities of the unsaturated zone to make it comparable to the electrical conductivities of the saturated zone is necessary, because the low conductivities of the unsaturated zone have major influence on the calculated electrical conductivity index.

The vulnerability mapping and vulnerability indices based on resistivity data provide a good tool to assess and quantify the protection of the groundwater resources.

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