Assessment of Groundwater Vulnerability and Pollution Risk using AVI Model, PSI and RGPI Indexes: Applied to Southern Gabes Aquifer System, Tunisia

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Abstract

Southern Gabes aquifer is part of coastal Jeffara plain located in southeastern Tunisia. It consists a semi-arid area in which groundwater is the main source to water supply for several socio-economic sectors. Southern Gabes aquifer suffers from excessive abstraction and heavy anthropogenic pressures that make local groundwater resources threatened by pollution risks. This study aims to assess groundwater vulnerability, evaluate and delineate groundwater risk regions. For this a 17 water samples were carried out in the study area and chemical composition were analyzed. A well-known AVI model has been used to assess aquifer vulnerability and new algorithms of sensitivity to pollution index (PSI) and risk groundwater to pollution index (RGPI) were implemented and used to assess, classify and mapping groundwater pollution risk. The method used in this study seems giving more precise results compared to conventional approaches. Moreover, this method allows assessing the pollution risk with flexible and reliable algorithm even with limited dataset. Results reveal that study area suffers from high risk. 41% of total surface of study area has a very high risk. Nonetheless only 30% of study area has a low to insignificant risk to pollution which necessitates taking severe precautions to protect the southern Gabes aquifer system. Hence, the poor natural protective capacity of study area needs a rapid intervention by local authorities in order to develop proactive solutions to protect and preserve groundwater resources from pollution risks and establish a long-term program for groundwater resources sustainable development.

Introduction

Water is abundant on the earth, but this vital resource is not evenly distributed. Many arid regions suffer from scarcity of surface water, which makes groundwater the only source of life to meet the social and economic needs, especially in developing countries. Groundwater is often exposed to sources of natural and anthropogenic pollution, which renders this resource unusable. Several studies have shown that excessive pumping, fertilizers and pesticides, industrial effluent discharge, and uncontrolled urban landfills as well as other human activities are major sources of groundwater pollution (Singh et al. 2015). Consequently, the scarcity and difficulty of obtaining potable water has become a serious problem in many regions of the world. Hence, it is important to maintain clean groundwater, protect it from pollution sources, avoid negative impacts on human health and ensure sustainable development.

This issue has been raised by many scientific works (Zhang et al. 2013; Abbasi et al. 2013; Signh et al. 2015) in order to find a solution to this life issue. Many research works have been done in different countries of the world to study the protection of groundwater for pollution, the first of which is Margat (1968) who identified this idea. Others have also attempted to determine the factors involved in assessing the vulnerability of aquifers such as the work of Albinet and Margat (1971).

Since, various assessment groundwater vulnerability methods have been developed elsewhere by different government agencies of water protection. A numerous of these methods have not received much international attention and they are generally not available. The groundwater vulnerability assessment methods are, therefore, multiple. To date, a numerous investigations have been undertaken at different countries and at different scales to assess the intrinsic groundwater vulnerability to pollution (Aslam et al. 2018). A comprehensive review of vulnerability assessment methods are presented in Moraru and Hannigan (2018) and Oke (2017). The most popular methods were AVI (Van Stempvoort et al., 1993), DRASTIC (Aller et al., 1987), GALDIT (Michaud et al. 2003) and RISKE (Giraud et al. 2000). These methods were overlay and index methods. They based on geologic, hydrogeologic, topographic and climatic parameters. They provide a thematic maps using GIS and convert parameters to vulnerability index, expressing a degree of vulnerability Al-Rawabdeh et al. (2014); Khodabakhshi et al. (2017) and Machdar et al. (2018). Others works have tried to improve some vulnerability index by integration some statistics method and artificial intelligence such as works published by Agoubi et al. (2018); Shouyu and Guangtao (2003).

Although, the DRASTIC method is the most common in most studies and popular, the Aquifer Vulnerability Index (AVI) method is widely used for assessing and mapping groundwater vulnerability. AVI method seems to be much easier and suitable method for aquifers in sedimentary environments (Anornu et al. 2012; Luoma et al. 2017) and requires only two parameters (the thickness of layers of vadoze zone and the hydraulic conductivity of each aquifer layer).

According to Van Stempvoort et al. (1993), the AVI method is shown as a dimension of time approach and represents the hydraulic resistance of an aquifer to vertical flow. On the basis of hydraulic resistances, the AVI vulnerability is divided into five classes from extremely low to extremely high vulnerability.

A review of the methods used to assessing the vulnerability of groundwater shows that the majority of methods make it possible to provide a vulnerability map of the aquifer and to determine the most vulnerable areas to pollution without quantifying the sensitivity of the groundwater to pollution. Therefore, the estimation of sensitivity to contamination is therefore a needful parameter for the risk assessment of contamination of groundwater.

The sensitivity of groundwater to pollution is a non-measurable concept depending on the parameters of the aquifer (Sinan et al. 2003). It makes possible to define a pollution sensitivity index (SPI) expressing the pollution that has already reached the aquifer from the unsaturated zone or from well and borehole.

Assessment of groundwater pollution quality purpose is closely related to human health and to save a lot of people from suffering from various diseases (Wegahita et al., 2020). Therefore, groundwater quality must be correctly assessed. Modern agriculture with extensive use of organic fertilizers and chemical industries, extensive use of detergents and uncontrolled waste dumps are among the most important causes of increased groundwater pollution. However, this has resulted in adverse and unexpected effects on groundwater quality. The rapid expansion of irrigated areas and the extensive use of fertilizers have also made groundwater pollution an environmental problem that needs a great deal of study.

Numerous studies have contributed to improve groundwater quality assessment. Some authors used methods include water quality index, groundwater chemical analysis and matter element extension analysis. Some of these methods is comprehensive and useful by scientists and hydrogeologists, however, others methods have a demerit due to their complex algorithms such as matter element extension analysis (Li et al., 2016; Li et al. 2018), Fuzzy comprehensive assessment method (Wegahita et al., 2020).

Assessing groundwater pollution risk is a key management in ensuring the health and safety of people. However, the risk of groundwater pollution is difficult to be measured in situ. It is governed by many factors and parameters that stimulate the risk. The risk is the result of a combination of vulnerability, threat and nature of the associated pollution (Uricchio et al. 2004; Asmael et al. 2021).

Mapping groundwater contamination risk areas can be threatened by serious problems due to the accuracy of the factors affecting the sensitivity of the aquifer to pollution. This approach needs to integrate the geological and hydrogeological data (aquifer productivity and hydrodynamics properties) and physicochemical groundwater properties. These parameters allow assessing groundwater pollution sensitivity and therefore the groundwater pollution risk expressed as Risk of groundwater to pollution index (RGPI). The RGPI will be used to express the final evaluation of groundwater risk to pollution and can used to delineate the risk degree of study area.

The specific objectives of this work were to (i) assess the vulnerability of groundwater to pollution in the southern Gabes region using the AVI method, (ii) quantify the sensitivity of groundwater to pollution and assessment of the groundwater risk pollution, (iii) delineate and map the areas at risk of pollution in the study area. A pollution and risk indexes to develop in this study will be complementary and make it possible to quantify the risk of groundwater pollution.

This study could be helpful for the local authority in making sustainable development decisions in order to protect groundwater and ensure its quality. This research may also help researchers to further develop scientific research methods to assess the risks of water pollution in many regions of the world.

Study Area

The study area corresponds to the southern Gabes region, located in the southeastern Tunisia, between parallels 37G3 and 37G6N and meridians 8G6 and 8G9E (Fig. 1). The study area covers an area of 1502.7 km². It is characterized by Mediterranean climate of predominantly semi-arid climate. The summer is very hot and a mild winter. Precipitation is irregular, both on an annual and seasonal scale. The annual average precipitation, over 28 years, is about 195 mm. The study area is characterized by a network of perpendicularly arranged faults, creating a domain of horst and graben (Mamou, 1990; Bouaziz, 1995).

It should be noted that the geological formations of southern Tunisia extend from the Permian to the Holocene (Rouatbi, 1967; Mamou, 1990; Bouaziz, 1995). The Cenomanian, Turonian and Coniacian limestone layers show a deep karstification (Rouatbi, 1967).

Analysis of local hydrogeological data shows that the surface aquifer is essentially formed by the alluvial quaternary; the Mio-Pliocene, much more clayey, is part of the superficial aquifer only by scattered conglomerate levels (Fig. 2). These two entities are of course connected by the wadis having dug their bed in the mio-pliocene. The quaternary aquifer can be considered as a free water table, while the Mio-Pliocene conglomerate levels are confined. The deep aquifer is formed from the limestone Coniacian. It is a confined aquifer; its roof is made up of several tens of meters of clay sediments of Mio-Pliocene age. In the direction of the Matmata foothills, however, several limestone units are flush upstream of this Matmata fault and can be considered as a groundwater recharge zone.

The limestone of the deep aquifer is strongly karstified (Ben Baccar, 1982), its porosity is of the order of 10%. Its average thickness is 60 meters. Its renewal rate is 94 years (Houriet, 2004).

Material And Method

2.1. Sampling water and analysis

Geochemistry is important step to highlight groundwater quality and mapping its salinity. Salinity is an indicator of groundwater sensitivity to pollution. Seventeen water samples were collected from wells and borehole from study area. Geographic positions and physical parameters (EC, pH, Salinity) were measured in situ and major ions were analyzed in geochemistry laboratory of institute of water sciences and techniques, University of Gabes. The samples location map is shown in Fig. 3.

2.2. Methodology flowchart

In this study, the aquifer vulnerability index (AVI), sensitivity to pollution index Index (PSI) and Risk of groundwater to pollution index (RGPI) were applied to assess groundwater vulnerability and risk to pollution. The AVI model is used according Van Stempoot et al. (1993). However, PSI and RGPI where a new developed index allowing assessment of the sensitivity to pollution and the risk of groundwater to pollution. The methodology used in this study is summarized in Fig. 4. The computation of AVI, SPI and RGPI were detailed below.

2.3. Aquifer Vulnerability Index model

The aquifer vulnerability index (AVI) is developed by Van Stempoot et al. (1993) as a method for assessing and mapping the groundwater vulnerability to pollution. AVI model used two parameters to quantify groundwater vulnerability:

- i. The thickness (d) of each sedimentary layer above the groundwater level,
- ii. The hydraulic conductivity (K) of each sedimentary unit.

The first parameter (d) of sedimentary units is derived from well-log and/or bore-hole data. Since K parameter may be determined for each sedimentary unit above piezometric aquifer level. At the second step, a hydraulic resistance (c) can be computed on the basis of d and K parameters. The factor c is a theoretical factor providing information on the travel time for water to move downward through the porous media above the uppermost saturated aquifer surface.

AVI measures the vulnerability according to the hydraulic resistance (c) to the vertical flow of water opposed by the geological formations located above the aquifer layer. A low hydraulic resistance (c) supposes a high vulnerability; on the contrary, high resistance supposes a low vulnerability. A vulnerability map can be deduced by calculating the logarithm 10 of the hydraulic resistance Log (c) for each of the inventoried points. The parameter c provides a vulnerability index from the relationship between the two factors of aquifer. The hydraulic resistance is computed as follow:

$$c = \frac{\sum_{i=1}^N d_i}{\sum_{i=1}^N K_i}$$

In which N is the number of layers and i: 1..N, di and ki are the thickness and hydraulic conductivity of layer number i.

The c has a dimension of time and represents the hydraulic resistance of an aquifer to vertical flow. The aquifer vulnerability is categorized, on the basis of hydraulic resistance, into five classes from extremely low to extremely high vulnerability (Table 1).

Table 1
AVI vulnerability classification on the basis of hydraulic resistance

Hydraulic Resistance (c)	Log(c)	AVI value	Vulnerability
0 to 10 years	< 1	1	Extremely high
10 to 100 years	1 to 2	2	High
100 to 1,000 years	2 to 3	3	Moderate
1,000 to 10,000 years	3 to 4	4	Low
> 10,000 years	> 4	5	Extremely Low

2.4. Pollution Sensitivity Index

Pollution sensitivity index (PSI) of groundwater is an indicator reflecting the sensitivity of aquifer to pollution. Previous studies, such as Sinan et al. (2003) and Rao et al. (2012) have considered that several factors can be considered in assessment of groundwater sensitivity to pollution. In this study, we take into consideration of the main parameters that controlling groundwater sensitivity. These factors will be detailed below:

Chemical index pollution: ICP

This factor is considered as a groundwater quality. Sinan et al. 2003 used only electric conductivity to express groundwater quality. Whereas Rao et al. (2012) used a pollution index of Groundwater (PIG) computed from groundwater chemical composition. In this study we will consider both EC and PIG for expressing the chemical index pollution. The EC express the global groundwater salinity and weighted 30% where the PIG express a specific salinity for each chemical element of groundwater composition, PIG is assigned 70% the Icp, because this parameter take into consideration a main factors controlling groundwater salinity.

$$I_{cp} = 0.3 \text{ Sec} + 0.7 \text{ PIG}$$

Where Sec is a rate (1 to 10) (Table 2) attributed to EC in accordance with its value; PIG is the pollution index of groundwater, according to Rao et al. (2012), The PIG parameter is computed as follows:

$$I_{cp} = \sum_{i=1}^n \frac{R_w}{\sum R_{wi}} \cdot \frac{C}{D_s}$$

Where Icp is chemical pollution index; n the number of chemical analyzed elements for each water sample; C is the concentration (mg/l) for each element of every water sample; and Ds is the permissible standard water quality (mg/l).

Table 2
Rate accorded to hydraulic conductivity (after, Sinan et al. 2003)

Electric conductivity C (μs/cm)	weight classes
< 400	10
400 to 1300	8
1300 to 2700	5
2700 to 3000	3
> 3000	1

Groundwater hydrodynamic index (IGH)

Hydrodynamic of groundwater is expressed by groundwater movement in aquifer. IGH is an important factor for assessing groundwater sensitivity to pollution. This parameter expresses the speed of groundwater flow which indicates the time of pollution dissipation from aquifer. This factor can be computed (after Sinan et al. 2003) as follows:

$$IGH = \frac{K \cdot i}{e}$$

In which IGH express the groundwater speed expressed (m/s); K is the Darcy permeability (m/s), i is the hydraulic gradient, and η_e is the effective aquifer porosity.

Hydrodynamic of aquifer can be classified into five on the basis of groundwater flow (Table 3).

Table 3
Weighting of effective
groundwater speed (after,
Sinan et al. 2003)

IGH (10^{-4})	Sensitivity classes
IGH ≥ 8	Very high
6 $\leq$ IGH < 8	High
4 $\leq$ IGH < 6	Moderate
2 $\leq$ IGH < 4	Low
IGH ≤ 2	Very low

Aquifer productivity index (IAP)

The aquifer productivity can be expressed by transmissivity, flow rate of the structures or by their specific flow rates. Five specific flow classes have been defined, to which the following ratings have been assigned:

Table 4
Specific productivity classes based on IAP

IAP (10^{-2})	weight
IAP ≤ 2	Insignificant sensitivity
2 $<$ IAP < 3	Low sensitivity
3 $<$ IAP < 4	Moderate sensitivity
4 $<$ IAP ≤ 5	High sensitivity
IAP > 5	Extremely high sensitivity

Sensitivity to pollution index (PSI)

Once the different classes have been defined and their scores assigned, the sensitivity index of the water table to pollution (Is) is calculated by adding the products of the score for each parameter used and its weight:

$$SPI = I_{cp} + I_{gh} + I_{pi}$$

The values of the SPI vary between 1 and 10 (Table 5) and expressing five classes of groundwater sensitivity to pollution resulting from the sum of three indexes expressing the chemical pollution, hydrodynamic of aquifer and aquifer productivity. Finally, the sensitivity map will be established. The final SPI map allows reporting the sensitivity to pollution spatial distribution and different classes of study area.

Table 5
Specific flow classes (after, Sinan et al. 2003)

PSI values	Sensitivity class of groundwater
≤ 2	Very low sensitivity
$2 < \text{SPI} \leq 4$	Low sensitivity
$4 < \text{SPI} \leq 6$	Medium sensitivity
$6 < \text{SPI} \leq 8$	High sensitivity
$8 < \text{SPI} \leq 10$	Very high sensitivity
$\text{SPI} > 10$	

Risk of Groundwater to Pollution index (RGPI)

A qualitative risk of groundwater to pollution has the subject of previous studies such as Zwahlen F.C. (2004) and Duda et al. (2020). They consider that the risk is a function of vulnerability of groundwater to pollution. Duda et al. (2020) used two factors to assess the overall risk as the sum of land use potential impact and intrinsic vulnerability to pollution.

A critical view of this method shows that only land use is insufficient to really express the risk of vulnerability, especially since several factors are responsible for the vulnerability of underground water. In this study, we consider the risk of groundwater to pollution (Risk of Groundwater to Pollution index: RGPI) can be calculated by the product of the AVI and the SPI.

$$\text{RGPI} = \text{AVI} \times \text{SPI}$$

It is thus clear from the product that the risk is greater the more the aquifer is vulnerable to pollution and the more sensitive it to this effect.

AVI ranked as 1 to 4 and SPI is ranked from 1 to 10, a result of these factor multiplication allows o classify RGP to five risk categories such as indicate in Table 6.

Table 6
Risk of groundwater pollution based on RGP index

RGPI	Risk classes
20 to 40	Very low risk (Green color)
40 to 60	Low risk (Blue color)
60 to 80	Moderate risk (Yellow color)
80 to 100	High risk (Orange color)
100 to 120	Extremely high risk (red color)

Results And Discussion

3.1. Groundwater chemical composition

The basic statistics of the physico-chemical parameters of groundwater in the study area are shown in Table 7. The standard deviation values are less than those of the mean for the totalities of the analyzed elements indicating heterogeneity of sampled water. Nevertheless, Kurtosis and skewness range from – 1.28 to 3.19 and – 1.34 to 1.78, respectively, suggesting a normal statistic distribution of analyzed data, except the Br has a kurtosis value of 3.19 indicating a leptokurtic distribution.

Table 7
Statistiques élémentaires des différents paramètres physico-chimiques mesurés

Statistique	Sal	CE	HCO ₃ ⁻	F ⁻	Cl ⁻	Br ⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺
N	17	17	17	17	17	17	17	17	17	17	17
Minimum	1.54	2.96	121.27	0.69	411.68	0.76	516.39	318.26	15.62	152.65	60.25
Maximum	7.55	13.14	161.23	1.26	2337.26	1.36	2718.59	1521.26	34.26	518.69	267.94
Moyenne	3.03	5.55	150.86	0.96	824.82	0.91	1119.23	568.15	23.19	271.38	111.47
Variance	2.64	7.67	99.95	0.03	251787.83	0.02	363183.33	91467.88	27.90	12732.11	2875.39
Ecart-type	1.62	2.77	9.99	0.17	501.78	0.14	602.65	302.44	5.28	112.84	53.62
Skewnes	1.30	1.24	-1.34	0.18	1.62	1.76	1.11	1.78	0.73	0.88	1.52
Kurtosis	1.06	0.84	1.86	-1.28	2.21	3.19	0.48	3.07	-0.47	-0.63	1.76

Correlation matrix (Table 8) provides a correlation coefficient between analyzed parameters. These coefficients highlight the relationship between elements dissolved in groundwater and provide information on factors controlling groundwater salinity. It is shown from Table 8 that the main ions controlling groundwater salinity are Cl, Na, SO₄, Ca, Mg and K suggesting the effect of rock-water interaction and evaporation impact. The bivariate correlation of Na, Cl and Ca, SO₄ and the relationship between salinity and (Na, Cl, SO₄, Ca) (Fig. 5) shows a high correlation ($R^2 > 0.9$) confirming the hypothesis above.

Table 8
Correlation matrix of analyzed elements of study area

Variables	HCO ₃ ⁻	F ⁻	Cl ⁻	Br ⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	EC	Salinity
HCO ₃ ⁻	1										
F ⁻	-0.72	1									
Cl ⁻	-0.56	0.83	1								
Br ⁻	-0.46	0.67	0.88	1							
SO ₄ ²⁻	-0.64	0.89	0.99	0.85	1						
Na ⁺	-0.55	0.82	1.00	0.90	0.98	1					
K ⁺	-0.58	0.83	0.93	0.71	0.95	0.91	1				
Ca ²⁺	-0.66	0.89	0.96	0.77	0.98	0.94	0.98	1			
Mg ²⁺	-0.56	0.83	1.00	0.86	0.99	0.99	0.95	0.97	1		
EC	-0.61	0.88	0.99	0.86	1.00	0.99	0.95	0.98	0.99	1	
Salinity	-0.60	0.87	1.00	0.87	1.00	0.99	0.95	0.98	0.99	1	1

It is showed from Fig. 6, Pie diagram, that the Na, Ca, Cl and SO₄ are the dominant groundwater ions in study area. SO₄ represents 36% of total ions, Cl is in the second order with 27%, Na represents 18 % and Ca. The chemical of groundwater composition indicates clearly that groundwater from study area is of type SO₄-Cl-Na-Ca.

3.2. Groundwater vulnerability index

Groundwater depth

According to the hydrogeological mapping presented in Fig. 7, the minimum and maximum depth of groundwater, as unsaturated zones, is 2 m and 40 m respectively. After topographic elevation, the minimum depth is north-east of southern Gabes. Figure 7 shows the depth class of groundwater. Five classes are presented: less than 5 m, 5 to 10 m, 10 to 20 m, 20 to 30 m and more than 30 m deep. The average depth of groundwater is located in Mareth, Zarat and Limoua which is 10 to 20 meters.

Groundwater vulnerability map using AVI method

According to resistivity measurements, the sub-surface consists of unconsolidated materials / alluvium such as clay to sand, sedimentary rocks (sandstone, limestone and clay). So, the decimal logarithm of the hydraulic conductivity is the range – 1.52 to 8.77. The highest hydraulic conductivity indicates excellent permeability, that is, from gravel to sand. Clay is the lowest coefficient of permeability in the study area.

There are five levels of groundwater vulnerability using the AVI method (Fig. 8), ranging from extremely low to extremely high vulnerability.

Areas of low to very high vulnerability are located to the east (Kettena, Limaya), west (Zerkine II), and south (Mareth) of the South Gabes area. The unsaturated zones are between 2 and 10 m; and with the exception of the western area of Mareth with a depth varying between 20 and 30 m. The hydraulic conductivity is between 10^{-3} and 10^3 m / day. This shallow depth which is accompanied with a high hydraulic conductivity of the unsaturated zone gives the aquifer a fragility in the face of climate change (high aridity and rare flows which Guaranteed in the aquifer, intense evaporation dependent on the lack of precipitation), and in anthropogenic activities (rapid infiltration of contaminants).

3.3. Pollution sensitivity index

The chemical index to pollution, hydrodynamic and productivity of aquifer and risk of groundwater to pollution were determined in accordance with the approach above adopted by authors. Results were adopted in Table 9. Spatial development map of risk indexes were shown in Figs. 9.a, 9.b, 9.c and 9.d, respectively.

A spatial development maps of IPC, IGH, IAP and SPI (Fig. 9), established by kriging techniques, have been validated by root mean squared error (RMSE) as information validation criterion. Computing RMSE of each factor of sensitivity assessment is of 0.92 for IPC, 0.16 for IAP, 0.93 for IGH and 0.66 for SPI. These values suggesting a robust estimation models results from spatial autocorrelation analysis.

Table 9
Results of sensitivity of groundwater to pollution

Well id	Chemical	Hydrodynamic	Aquifer	Sensitivity	AVI	Risk to pollution
	sensitivity	sensitivity	productivity	To pollution	(log c)	
	IPC	IGH	IAP	SPI	AVI	RGPI
1	2.34	2.65	0.08	5.07	8	40.54
2	5.38	3.6	0.11	9.09	6.43	58.45
3	6.8	2.6	0.03	9.43	6.13	57.81
4	2.18	1.43	0.06	3.67	0.37	1.36
5	2.06	2.5	0.36	4.92	6.47	31.84
6	2.4	0.61	0.05	3.06	6.17	18.87
7	5.19	2.5	0.04	7.73	6	46.35
8	2.39	2.17	0.12	4.68	5	23.38
9	5.46	3.85	0.07	9.38	6.3	59.06
10	2.33	6	0.05	8.38	6.77	56.71
11	3.04	1.35	0.19	4.57	6.47	29.59
12	2.42	4.86	0.54	7.81	8.77	68.52
13	2.58	3.32	0.48	6.39	6	38.32
14	3.03	2.76	0.58	6.37	6.96	44.34
15	4.11	2.85	0.38	7.34	7	51.41
16	4.97	2.5	0.36	7.83	1.09	8.54
17	4.3	3.5	0.01	7.82	7	54.72

SPI is reported versus each sample (Fig. 10). It shown from Fig. 10 that study area presents four class of sensitivity to pollution ranging from low to extremely sensitivity. Whereas, 12% of total study area has a low sensitivity, 24 % has a medium sensitivity, 41 % is in the high class of sensitivity and 24 % of total surface has an extremely sensitivity to pollution.

Risk of groundwater pollution RGPI

The RGPI is computed according the above method. Results were reported in Fig. 11. These findings show clearly that study area is classified into five risk classes. The first class is insignificant risk represent a 18% of study area. The second class is of 12% and considered as low pollution risk. Nevertheless 18% has a medium risk, 12% of the total surface showing a high risk. The fifth class represents a 41% of total area and considered a very high risk to pollution.

The spatial development of risk to pollution has been mapped (Fig. 12) and estimation method is validated using RMSE information criterion. A RMSE value is quite little suggesting a perfect model for RGPI estimation.

It is shown from Fig. 12 that coastal and central part of study area has an extremely to high risk to pollution. These parts of study area consist to a plain with important aquifer productivity in which agriculture is the most developed. In addition, its position close to the Mediterranean coast favors saltwater intrusion and threatens the groundwater quality. However the western part shows a moderate to very low risk. This part is formed by uplands (hills and mountains), where the slope is important, which minimizes groundwater recharge and, consequently, reduces the groundwater contamination.

The use of AVI, PSI and RGPI as indicators of groundwater vulnerability, sensitivity to pollution and risk of groundwater to pollution is an important approach to assess the global groundwater risk to pollution. Results of this study demonstrate the importance of groundwater risk assessment and delineation of risk areas in decision making for groundwater sustainable management.

Compared with previous studies, indicators used in this study showed great importance in groundwater risks assessment. The novel approach considers geological, hydrogeological characteristics and groundwater chemical composition as well as aquifer productivity and hydraulic conductivity. This makes the accuracy of determining the indicators more suitable compared to the many published studies (Sinan et al. 2003; Rao et al. 2012, Kourgialas and Karatzas, 2015; Asmael et al. 2021) that have adopted the assessment of the characteristics of the aquifer without considering the relevant factors.

Conclusion

Assessment and delineation of aquifer risk areas is critical to the management of groundwater and water supply in both urban and rural areas. Indicators of groundwater vulnerability and sensitivity to pollution have been studied using AVI a well-known model and developing new indicators based on the groundwater sensitivity (PSI) to natural or anthropological pollution, as well as an indicator for calculating the risk that threatens groundwater resources (RGPI).

Results led to the fact that the adoption of such indicators enables the identification of pollution risk areas more accurately and the uncertainty in determining the data, especially if the dataset is limited.

In this study AVI, PSI and RGPI have been used and validated to assess the groundwater risk pollution to southern Gabes aquifer. Results revealed that five classes of groundwater risk to pollution have been identified based on aquifer vulnerability, sensitivity to pollution and risk of groundwater to pollution indexes. Study area has been classified into five risk classes: 18% insignificant risk, 12% low risk, 18% a medium risk, 12% a high risk and 41% as very high risk to pollution. The highest risk to pollution is showed in central and coastal part southern Gabes basin. This region is characterized by alluvial sediments filling the Jeffara plain and constitutes a high permeable aquifer with an important hydraulic productivity. In addition, this area is a coastal area very vulnerable to seawater intrusion.

Finally, this study provides a framework that's his benefit lies in assessing the risks of groundwater pollution by calculating an accurate and reliable indicators that can be easily applied in areas with complex environments where data is usually limited.

Delimiting and mapping the aquifer system risk zones is an effective tool in protecting and saving groundwater resources, especially in arid areas in which groundwater is the unique life source, as well as an important tool in decision-making for planning and use of groundwater and good management of water resources. Despite its simplicity and uncomplicatedness, this method can be an effective tool for the management of groundwater resources for sustainable development in the study area and similar areas in many parts of the world.

Declarations

Author contribution The authors significantly contributed in preparing, writing and revising the manuscript. Mounir Atoui: sampled water, data collect and analysis, conceptualization, writing the original draft, and formal analysis. Belgacem Agoubi: resources and writing-review and editing.

Data availability The datasets used and analyzed during the current study are available from the authors on reasonable request.

Code availability Not applicable.

Declarations Ethics approval Not applicable.

Consent for publication Not applicable

Consent to participate Not applicable

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Figures

Figure 1

Location and geological maps of study area

Figure 2

Geological cross-section A-A' from study area (modified, after Houriet, 2004)

Figure 3

Location map of sampled water in study area

Figure 4

Flowchart of the method adopted in this work

Figure 5

Relationship between Salinity and Cl, Na, SO₄ and Ca

Figure 6

Pie diagram of the main concentration of major ions in study area

Figure 7

Groundwater depth in study area

Figure 8

Groundwater resistance map in study area after AVI method

Figure 9

Spatial development maps of sensitivity to pollution of study area. (a) Sensitivity to chemical pollution, (b) sensitivity based on hydrodynamic of aquifer, (c) sensitivity based on aquifer productivity, and (d) global sensitivity to pollution index SPI.

Figure 10

SPI vs. samples showing a groundwater classification on the basis of sensitivity of groundwater to pollution.

Figure 11

Classes and percentage of each risk to pollution classes from study area

Figure 12