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Original Research

Comparative Assessment of Groundwater Vulnerability to Pollution in a Semi-Arid Area Using DRASTIC, SINTACS, GOD, and SI Methods: A Case Study of the Ank Djamel Watershed, Northeastern Algeria

Horiya Bouali[1, 2]*, Mahrez Boulabeiz[1], Dounia Dib[1, 2], Sofiane Idir[3], Fatma Slimani[1, 2]

[1]Department of Ecology and Environment, Faculty of Natural and Life Sciences, Abbes Laghrour University, Khenchela, PO BOX 1252 Road of Batna, Khenchela -40004-Algeria
[2]Biotechnology, Water, Environment and Health Laboratory, Abbes Laghrour University, Khenchela, PO BOX 1252 Road of Batna, Khenchela -40004- Algeria
[3]Laboratory of Applied Zoology and Animal Ecophysiology, Abderrahmane. Mira University of Bejaia, Targa Ouzemour, Algeria

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Abstract

This study focuses on the Ank Djamel watershed, a semi-arid region located in northeastern Algeria, with the objective of mapping vulnerability to pollution to enhance groundwater management. To achieve this, a comprehensive database was compiled from various sources, including geological, hydrogeological, geomorphological, climatic data, and satellite imagery. Four different methods are applied using a geographical information system (GIS): DRASTIC, SINTACS, GOD, and SI. The SI and SINTACS methods revealed three main vulnerability classes: low, medium, and high. The GOD model identified three classes as well: very low, low, and moderate. In contrast, the DRASTIC model identified four classes: very low (18.47%), low (26.38%), moderate (38.46%), and high (16.28%). The accuracy of the models was assessed through a comparison of nitrate observation value with the estimated pollution vulnerability in the measured wells. the DRASTIC and SI methods emerged as the most reliable for assessing groundwater vulnerability in the Ank Djamel watershed, while the SINTACS method provided complementary information. The GOD model was found to be less suitable for the studied area.

Keywords: Groundwater, vulnerability, GIS, semi-arid, Northeastern Algeria

*e-mail: horiya.bouali@univ-khenchela.dz

Introduction

Freshwater scarcity remains a critical global challenge and underscores the paramount importance of responsible management and protection of groundwater resources. Groundwater supports ecosystems and enables various socio-economic activities, such as agriculture, industry, and domestic use [1]. It also serves as a vital source of drinking water for billions of people. However, its inherent vulnerability to various contaminants compromises its quality and sustainability. Consequently, groundwater vulnerability assessment has become an essential tool for informed decision-making in aquifer management and the protection of human health [2]. Recently, there has been a noticeable increase in significant contamination of both surface and groundwater, adversely impacting the well-being of rural farming communities and nearby livelihoods [1-3], Assessing the vulnerability of groundwater aquifers serves as a foundation for implementing initial protective measures for critical groundwater resources. Typically, this evaluation represents the initial phase in assessing groundwater pollution hazards and quality when it is a concern [4, 5]. The protection of groundwater in the semi-arid regions of Algeria is of utmost importance for several compelling reasons [6]. Firstly, these areas have a semi-arid climate characterized by rare rainfall and scarce surface water resources, underscoring the critical role of groundwater in meeting water supply needs, supporting agriculture, and sustaining industrial activities [7, 8]. Furthermore, agriculture in Algeria is heavily dependent on groundwater for irrigation, especially in the northern regions, making groundwater protection essential to maintain agricultural productivity and ensure food security [9].

In addition to its pivotal role in supporting various sectors, groundwater in these regions is vulnerable to contamination from natural sources or pollution, posing a potential threat to public health and the environment [10]. Finally, given global concerns about water scarcity and pollution, groundwater protection becomes even more important in semi-arid regions where water resources are naturally limited [11].

Safeguarding groundwater in these areas is essential not only to ensure a reliable and sustainable water supply but also to protect the fragile ecosystems that rely on these vital resources [12]. The Ank Djamel watershed, located in the Batna and Oum El Bouaghi regions, faces several challenges related to groundwater. Overexploitation of groundwater for agricultural irrigation is a major issue in these regions and leads to groundwater decline [13]. Groundwater pollution from industrial activities is also a growing concern, as it can have negative impacts on public health and the environment. Furthermore, salinization of aquifers is a significant problem due to low rainfall and excessive use of fertilizers and pesticides [14].

Management and monitoring of groundwater resources in these regions is often inadequate, leading to overexploitation and degradation of water quality [15]. Studies were conducted to assess the vulnerability of groundwater to pollution in the Ank Djamel watershed. They examined the processes and factors affecting groundwater quality and identified the areas most vulnerable to contamination [16].

The aim of this assessment is to provide essential information for the sustainable management of groundwater resources, and for the protection of the environment and public health[17].

The susceptibility of groundwater to contamination or pollution depends on various factors, including soil characteristics (such as soil structure, texture, and infiltration rate), hydrological features (like drainage density, runoff volume, and slope), climatic conditions in the region, land use patterns, and the characteristics of the pollutants entering the groundwater [1-18].

This study focuses on the Ank Djamel watershed, a basin located in the high plateaus of Constantinois in northeastern Algeria. It uses various methods to assess groundwater vulnerability to pollution, including DRASTIC, SI, GOD, and SINTACS, and uses Geographic Information Systems (GIS) to identify areas that are vulnerable but not currently exposed to pollution. The necessary data were collected from the water resources departments of the wilayas of Batna and Oum El Bouaghi, as well as online portals such as the USGS for Digital Elevation Models (DEM) [18, 19]. The maps created for each parameter were classified and combined based on the models. The results of these methods for each classification range from low to high vulnerability in the groundwater quality study [20].

This research delves into the complex processes influencing groundwater vulnerability, aiming to advance our understanding and provide valuable insights for sustainable water resource management. The specific objectives of our study are as follows:

To comprehensively assess the intrinsic vulnerability of the target aquifer(s) using established or novel methods that take into account important hydrogeological, hydrochemical, and geomorphological factors. Delineate and prioritize vulnerable zones within the study area based on their susceptibility to contaminant infiltration and their potential risk to groundwater quality. To assess the influence of anthropogenic activities and potential sources of contamination of groundwater vulnerability, requiring the integration of land use practices, agricultural inputs, and industrial processes. Develop well-informed recommendations and strategies for groundwater protection and sustainable resource management, with the aim of informing stakeholders such as policymakers, water managers, and local communities, thereby contributing to the long-term viability of these resources [21].

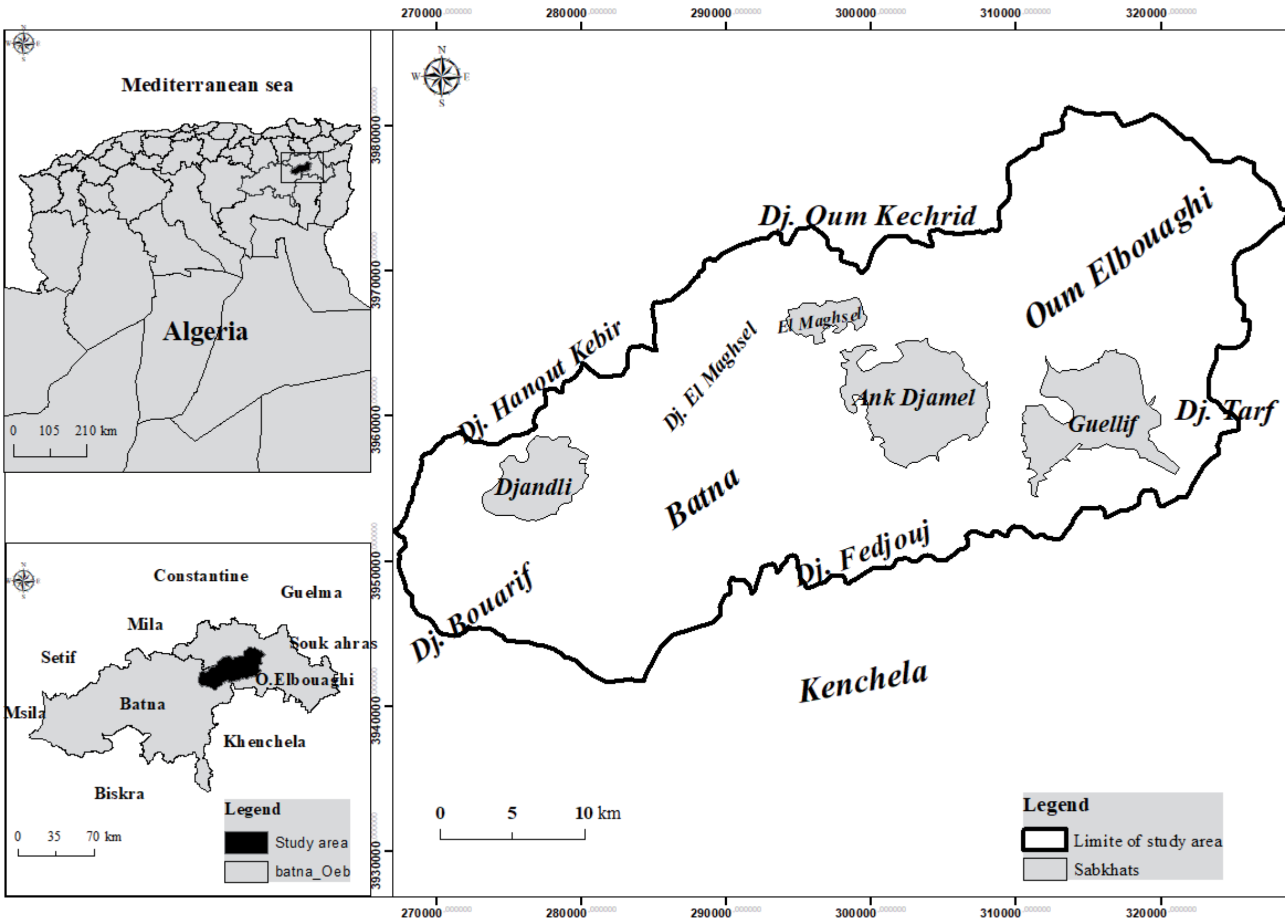

Fig. 1. Location map of study area: the Ank Djamel watershed in northeastern Algeria.

Material and Methods

Study Area

The study area covers the entire Ank Djamel basin (Fig. 1), situated between 35°58'0" and 35°35'0" North latitudes and 7°7'0" and 6°25'0" East longitudes in the northeast region of Algeria. It forms part of the broader western.

Oum El Bouaghi and eastern Batna states, characterized as an inter-mountainous plain within the Constantine high plateau basin. Covering an area of 1232 km^2, the Ank Djamel basin is surrounded by mountain ranges: Djebel Maghsel and Djebel Ank Djemel to the north, which are part of the Oum Kechrid range, Djebels Fedjoudj and Sidi Khiar to the south, and the Batna uplands to the southwest. To the east, it is bounded by Garaet Taref and the Fkirina Plain, while to the west, it is bounded by the Ain Yagout and Boumia Plain [22].

The lithological nature and behavior of the underlying soils in the study area are identified using sections of existing boreholes. This enables an understanding of soil geometry, stratigraphy, and petrography [14, 20, 23-25]. Geologically, quaternary formations cover most of the study area. These formations consist mainly of sabkhats, ancient silts, consolidated dunes, and sands, followed by polygenetic glacis, scree, alluvium, silts, and gravels.

In the northern part of the study area, Miocene formations consist of clays, conglomerates, and lacustrine limestones. The watershed is surrounded in its southern part by Cretaceous limestones, forming the Fedjoudj, Tarf, and Bouarif mountains. In addition, Triassic outcrops are observed in the central and northwestern parts of the area [20, 24, 26] (Fig. 2).

The study area falls within the semi-arid climate domain, which is characterized by cold winters and hot, dry summers. The average annual temperature is 15.03°C, and the average annual precipitation is 459.39 mm. Within the Ank Djamel basin, the river network is less developed due to the region's semi-arid conditions, resulting in predominantly temporary tributaries. However, amidst these seasonal watercourses, the permanent Chemora River stands out. Analysis of the river network map shows clear seasonal hydrological patterns, typically characterized by a period of river filling occurring during fall and winter. Water availability in the region is strongly influenced by climatic factors, which directly affect the flow conditions of the rivers that supply the region. The drying out of the region is primarily due to evaporation, which is particularly pronounced from April onwards.

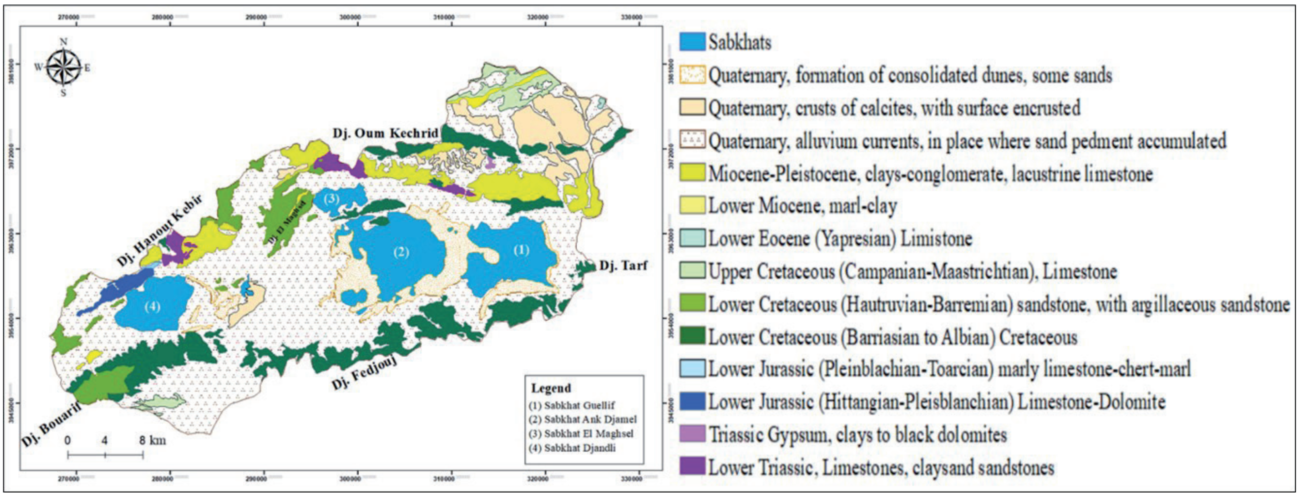

Fig. 2. Geological map of Ank Djamel basin (Adapted from geological map of Algeria 1976).

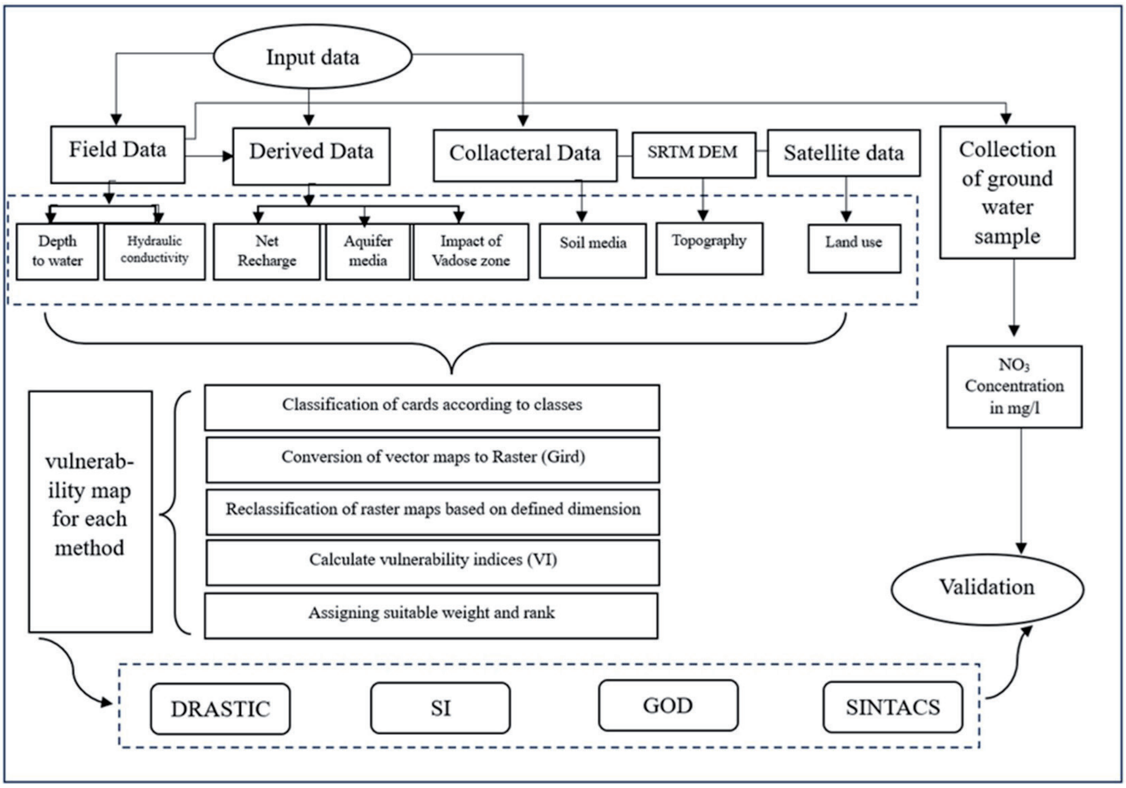

Fig. 3. Flow chart for groundwater vulnerability assessment.

Methodology

To assess the contamination vulnerability zones within the Ank Djamel watershed, four different methodological approaches were implemented using Geographic Information System (GIS) software and tools (Fig. 3). ArcGIS 10.8 software developed by Esri (Environmental Systems Research Institute, Inc.) was utilized. ArcGIS Desktop includes a range of integrated applications: Arc Map (for data analysis and cartographic product creation), Arc Catalog (for database management and navigation), and Arc Toolbox (for data conversion, manipulation, processing, and analysis). With these three applications, all GIS tasks can be performed, from the simplest to the most advanced. In the present study, the evaluation of groundwater intrinsic and specific vulnerability includes the implementation of the following methods: DRASTIC, SINTACS, GOD, and SI. The specific vulnerability was evaluated using the SI model, while the intrinsic vulnerability was assessed using DRASTIC, SINTACS, and GOD models. All the data and maps were converted into a raster dataset with a cell size of 30 m × 30 m.

DRASTIC Method

Developed through a collaborative agreement between the National Water Well Association (NWWA) and the United States Environmental Protection Agency (USEPA) [27]. The abbreviation DRASTIC signifies the primary initials of the seven factors that determine the vulnerability index [28-30].

Each parameter is assigned a weighting factor ranging from 1 to 5, based on its increasing significance level [31]. These parameters are further divided into ranges and rated on a scale of 1 to 10, with 1 being the lowest potential for contamination and 10 being the highest. The assigned score reflects the importance of each factor in quantifying vulnerability (Table 1) [32]. The DRASTIC index is determined using equation (01)

$$DRASTIC = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (1)$$

where D, R, A, S, T, I, and C indicate the seven parameters of the method, while indices w and r represent the weight of each parameter and the corresponding rating, respectively.

SI Method

The Susceptibility Index (SI) method [33] assesses the specific vertical vulnerability to pollution, focusing on agricultural activities, particularly nitrates. It extends the DRASTIC method by incorporating four original parameters (depth to water, annual effective recharge, aquifer media, and topography) and introduces a new parameter: land cover type, classified according to the CORINE Land Cover classification [34].

The Sensitivity Index (SI) method assesses the vulnerability of the aquifer by considering five parameters: groundwater depth (D), net effective recharge (R), aquifer lithology (A), topography (T), and land use (LU), as defined by Equation (02) [35-38].

$$SI = DrDw + RrRw + ArAw + TrTw + LUrLUw \quad (2)$$

where SI denotes the Sensitivity Index and r and w indices are the rank and weight of the layer, respectively [32]. The land use in the study area is an important parameter in assessing vulnerability to pollution.

Each land use class is assigned a value known as the Land Use Factor (LU), which ranges from 0 to 100. It is important to note that the scores assigned to the different parameter classes were multiplied by 10 to facilitate the interpretation of the result. Therefore, these values range from 0 to 100 and indicate the least to most vulnerable conditions (Table 1) [39].

GOD Method

The GOD method, developed in 1987 by Foster in the United Kingdom, is widely used as a parametric vulnerability assessment approach. This methodology was specifically developed for regions where there is a lack of sufficient information about the subsoil and groundwater [40].

It includes only three parameters: the type of groundwater confinement (G), the general lithological characteristics of the vadose zone (O), and the depth of the groundwater table (D). The GOD index is determined using Equation (03). Its values range from 0 (indicating negligible vulnerability) to a maximum of 1 (indicating extreme vulnerability) [41, 42].

$$GOD = G \times O \times D \quad (3)$$

SINTACS Method

SINTACS is an intrinsic vertical vulnerability method formulated by Civita (1990) [43]. It represents an adaptation of the DRASTIC method to the hydrogeological, climatic, and impact conditions characteristic of the Italian territory and the Mediterranean basin [42-44]. The SINTACS method takes into account the same parameters as the DRASTIC method [45]. What distinguishes the SINTACS method from DRASTIC is the consideration of five different scenarios: normal impact, significant impact, drainage from a shallow network, deep karstified terrain, and fissured terrain [46]. The SINTACS index values are divided into four classes, corresponding to four levels of vulnerability (Table 1) [47-49].

Data Collection and Processing

All necessary parameters are related to the physical properties of the main aquifer, which serves as the primary groundwater resource in the region, were acquired from the 351 operational wells within the area. The remaining data were extracted from a digital elevation model (DEM), geological map, soil map, and Sentinel 2A land use images. Using the ArcGIS 10.8 software, a raster map is created by interpolating and digitizing the terrain data for each indicator from the previously created geodatabase (Table 2). These software tools enable the analysis and processing of extensive geospatial data and facilitate the development of aquifer vulnerability maps. They support multi-criteria analyses and the updating of developed models [50].

To determine the vulnerability indices, each indicator is assigned an appropriate weight and score based on the formula specified in each specific vulnerability assessment method.

Groundwater vulnerability parameters

The assessment of the various parameters considered in the DRASTIC, SINTACS, SI, and GOD methods

Table 1. Vulnerability assessment criteria for the DRASTIC, SI, GOD, and SINTACS methods.

Vulnerability	DRASTIC	SI	GOD	SINTACS
Very high	> 200	> 85	0.7–1	> 210
High	161–200	65–85	0.5–0.7	186-210
Moderate	121–160	45–64	0.3–0.5	105-186
Low	80–120	< 45	0.1–0.3	<105
Very low	< 80	-	-	-

requires a thorough understanding of the natural environment. The details of each thematic layer are described below [51].

Depth to Water

The depth to groundwater from the surface is a crucial factor in determining the thickness of the unsaturated zone. This unsaturated zone represents the layer through which infiltrating water must travel before reaching the water table or the saturated zone below [52, 53].

Greater groundwater depth means that pollutants must pass through and be attenuated by a thicker unsaturated zone [37, 54].

According to the water depth map (Fig 4a), the eastern and western zones of the basin are characterized by significant water depths, reaching up to 110 meters. The water depth gradually decreases toward the middle of the basin, especially in the southern part (south of Sabkhat Guellif and Ank Djamel).

Net Recharge (R)

Net recharge is the volume of water per unit area that enters and reaches the groundwater table [55], expressed in millimeters per year. Recharge takes into account the average annual infiltration but does not consider the distribution, intensity, or duration of recharge events [56]. Although recharge is a crucial factor affecting groundwater contamination potential, it is one of the least understood parameters. It varies both spatially and temporally and is difficult to measure directly [57]. In the study area (Fig. 4b), net recharge was calculated based on the water balance and the hydrological soil type [58]. The highest values are observed in the eastern parts of the study area, with an average of 41.83 mm. Towards the middle of the basin, the recharge values drop to

Table 2. Data sources and processing mode of different parameters (DWR: Direction of Water Resources).

Parameters	Type of data	Data processing	Data sources
Depth to water	Point	Interpolation	Lithological Borehole Cross-sections (DWR of Oum Elbouaghi and Batna);
Net recharge	Polygon	Digitalization	Rainfall and Average Monthly Temperatures (From 1992 to 2022)
Aquifer media	Polygon	Digitalization	Lithological Borehole Cross-sections (DWR of Oum Elbouaghi and Batna); Hydrogeological Map of the Alger Region at 1/200,000 Scale, K. Achi, 1973 (ANRH Alger).
Soil media	Polygon	Digitalization	Soil Map of Algeria (TEBESSA) at 1/500,000 Scale
Topography	Polygon	Digitalization	Digital Elevation Model (DEM)
Impact of the vadose zone	Point, Polygon	Interpolation, Digitalization	Lithological Borehole Cross-sections (DWR of Oum Elbouaghi and Batna); Geological Maps of Oum El Bouaghi, Ain Kercha, Garaet Et Taref, Ain El Ksar, Boulehilet, and Ain Yaghout at 1/50,000 Scale)
Hydraulic conductivity of the aquifer	Point	Interpolation	Lithological Borehole Cross-sections (DWR of Oum Elbouaghi and Batna); Geological Maps (Oum El Bouaghi, Ain Kercha, Garaet Et Taref, Ain El Ksar, Boulehilet, and Ain Yaghout at 1/50,000 Scale)
Lund use	Point, Polygon, Polyline	Digitalization	Sentinel 2 satellite imagery

22.05 mm, while in the western parts, the calculated net recharge is 25.53 mm.

Aquifer Media (A)

Aquifer media refers to consolidated and unconsolidated rock that serves as a reservoir for water storage. Properties of aquifer media, such as pore spaces and grain size, influence water flow and movement of contaminants within the aquifer [59]. Data on the lithology of the aquifer were obtained from stratigraphic records of boreholes.

The aquifer lithology in the western part of the study area (Fig. 4c) consists of limestone, sandstone, dolomite, and clay. Gravel and sand occur in small proportions in the center of the basin and in the northeast, while clay and conglomerate are present in the eastern part and certain central-western regions of the basin.

Soil Media (S)

Soil properties have a significant impact on the amount and quality of water that can percolate to recharge groundwater, and thus impact the possibility of pollutants migrating vertically through the unsaturated zone above the water table [60]. It also influences the migration time of pollutants towards groundwater [61]. A soil permeability map of the study area was created using the soil map of Algeria (Tebessa) at a scale of 1:500,000 (Fig. 4d). There are four soil types: saline soils, which are characterized by the presence of clayey and saline sediments in Sabkhats and occur mainly near the Sabkhats, such as Ank Djamel, Guellif, El Maghsel and Djandli; calcareous soils found in the central-south of the basin and in the western part; Limestone soils covering the northern part and extending east and west; and alluvial soils, located in the middle of the basin between Sabkhats, Ank Djamel and Djandli.

Topography (T)

The topography index (T) takes into account the influence of land surface properties on the leaching mechanism. Precipitation produces three water balance components: runoff, recharge, and evapotranspiration. The balance between these components is controlled by the local conditions of climate, topography, and hydrogeology. Therefore, the topography index represents a qualitative indication of the relationship between runoff and infiltration, based solely on the slope of the terrain [62].

The topographic data for the study area was derived from a digital elevation model DEM

The variation in terrain slope controls the possibility of pollutant infiltration. It is assumed that the lower the gradient, the greater the infiltration, and the more vulnerable the area becomes. The majority of the study area (Fig. 4e) has gradients between 0% and 6%, which, according to the underlying assumption, makes it more vulnerable to groundwater contamination. In contrast, the areas with gradients greater than 12%, which are in the minority in the study region, are considered less vulnerable to pollution infiltration.

Impact of Vadose Zone (I)

The vadose zone is the unsaturated layer above the water table or unconfined aquifer. Cracks, joints, and pores in its grains serve as a seepage medium for water to reach the aquifer. This layer is a crucial parameter influencing groundwater vulnerability, akin to the soil and aquifer types in an area. A thicker vadose zone decreases pollutant movement to groundwater, while a thinner zone enhances vulnerability. This parameter has been given the highest weight (5) in the assessment of groundwater vulnerability according to its critical importance [42].

Vadose zone data was collected from stratigraphic wells logs and then divided into sub-classifications according to their ability to admit and transmit water.

The western part of the study area (Fig. 4f), which consists mainly of silt- and clay-bearing gravel and sand, received the highest rating score. In the central and eastern parts, the vadose zone consists of limestone, sandy clays, and gravel clay, with smaller proportions of clay and marl, resulting in medium and lowest ratings, respectively.

Hydraulic Conductivity of the Aquifer (C)

Hydraulic conductivity refers to the aquifer's potential to transport water; therefore, this parameter expresses the velocity of contaminant movement in the aquifer, with aquifers having high hydraulic conductivity being more vulnerable to pollution sources [63].

For this parameter, reference was made to previous studies [64] and pumping tests, which are documented in the technical data sheets of the drillings carried out in the study area.

Analysis of hydraulic conductivity data (Fig. 4g) revealed that the aquifer system predominantly has moderate hydraulic conductivity, which ranges from $0,2 \times 10^{4-}$ m/s in the south to $0,58 \times 10^{4-}$ in the northern part of the basin. Hence, it means that there is an increase in hydraulic conductivity towards the north of the study area. This variation can be explained by the presence of fissured limestone formations in the aquifer.

Lund Use (LU)

Land use includes both natural and human activities that occur on the land surface. In many regions of the world, groundwater is significantly influenced by various types of land use, including agricultural, urban, and industrial activities. Anthropogenic activities and agricultural practices are the main sources of groundwater pollution.

A parameter known as the Land Use Factor (LU), which ranges from 0 to 100, is assigned to each land use class. It should be noted that the ratings assigned to the classes of various parameters have been multiplied by 10 to facilitate the interpretation of the results. Consequently, these values range from 0 to 100, indicating varying degrees of vulnerability from least to most [39].

The land use map of the study area (Fig. 4h) was derived from an LC/LU (Land Cover Land Use) classification [63] using Sentinel 2 satellite imagery. According to the Corine land cover classification, 9.73% of the study area is used for agricultural, pasture, and agroforestry purposes, 0.46% is conserved as forest and semi-natural lands; 29.06% is preserved as quarry and shipyard and the remaining 8.12.% is open water and other uses.

Type of Aquifer (G)

Characterizing the typology of an aquifer is a crucial factor in assessing the susceptibility of groundwater resources to potential contamination. It can be recognized from the subsurface geological conditions determined by analyzing well log data analysis and mapping water level [65]. In the study area (Fig. 4i), the aquifer transitions from unconfined to semi-confined in the northeast and becomes fully confined toward the southwest.

Vulnerability Maps and Nitrate Spatial Distribution

The study area has a predominantly agricultural character, which means that the groundwater is exposed to a risk of contamination, especially by nitrates due to the excessive use of industrial and natural fertilizers.

The spatial distribution of nitrates in groundwater in the study area (Fig. 5) allows the identification of contaminated zones and allows correlation with the vulnerability assessment methods used in this study. Additionally, it helps determine the most appropriate method. However, it is important to recognize to acknowledge the limitations of this comparison. Determining the most appropriate method should be undertaken with caution, and taking into account the potential limitations and uncertainties associated with the data or methodological approaches used.

In this study, the nitrate concentration ranges from 5 to 135 mg/l. In the northeast and northwest of the study area, the nitrates' concentration in groundwater is between 50 and 139 mg/l, indicating strong contamination linked to intense agricultural activity. In the rest of the study area, the concentrations are below 50 mg/l.

Results and Discussion

DRASTIC vulnerability map shows four levels of aquifer vulnerability, ranging from very low to high (Fig. 6a). There is a very low risk in the western and southern parts, which accounts for 18.47% of the total area. Low vulnerability, covering 26.38% of the total area, covers the extreme northeast of Sabkhat Guellif, the center of the basin, and a significant part of the western part. The moderate vulnerability covers 38.46% of the study area, and includes the eastern part, extending to the middle of the basin and reaching east of Sabkhat Djandli. The high vulnerability zone, which occupies 16.68% of the study area, is located in the north and center, where the groundwater depth is low and the hydraulic conductivity is high.

The obtained SI map (Fig. 6b) shows an SI range from <45 to 84, indicating three degrees of aquifer vulnerability, ranging from low to high. The low vulnerability class presents 34.10% of the study area and is justified by the presence of impermeable soils such as sabkhats (impermeable soils) and mountainous regions. The medium vulnerability class covers 31.53% of the basin and corresponds to pastures and agro-forest zones. The high vulnerability class occupies 34.37% of the study area and is located in the northern and southern parts of the basin, which are agricultural areas with shallow groundwater and high hydraulic conductivity.

The land use parameter plays an important role in determining the groundwater pollution sensitivity levels in the SI method, which can explain the detailed classification in the map obtained by this method.

The GOD vulnerability map (Fig. 6c) reveals three vulnerability classes: very low (0-0.1), low (0.1-0.3), and moderate (0.3-0.5).

The area with very low vulnerability, comprising 38% of the total region, is located in the eastern part of the basin and is associated with a confined aquifer. In the central part, which represents 30% of the study area, the vulnerability class is low due to the semi-confined nature of the aquifer and moderate groundwater depth. The moderate vulnerability class represents 32% of the study area, which is due to the confined nature of the aquifer and the significant depth of the groundwater.

The GOD method takes into account the depth to the groundwater surface and the properties of the vadose zone. Topographic variability and geomorphological factors may explain differences in aquifer vulnerability. The relationship between vulnerability and terrain suggests that plateaus or elevated topographic elevations may provide greater protection from groundwater contamination.

The SINTACS index map (Fig. 6d) categorizes the vulnerability levels of the study area into three classes: low, medium, and high. Areas of low risk (20%) are found in the western region and sporadically in the south, east, and extreme northeast of the basin. The medium vulnerability class (63%) covers most of the catchment area, with the exception of the eastern and

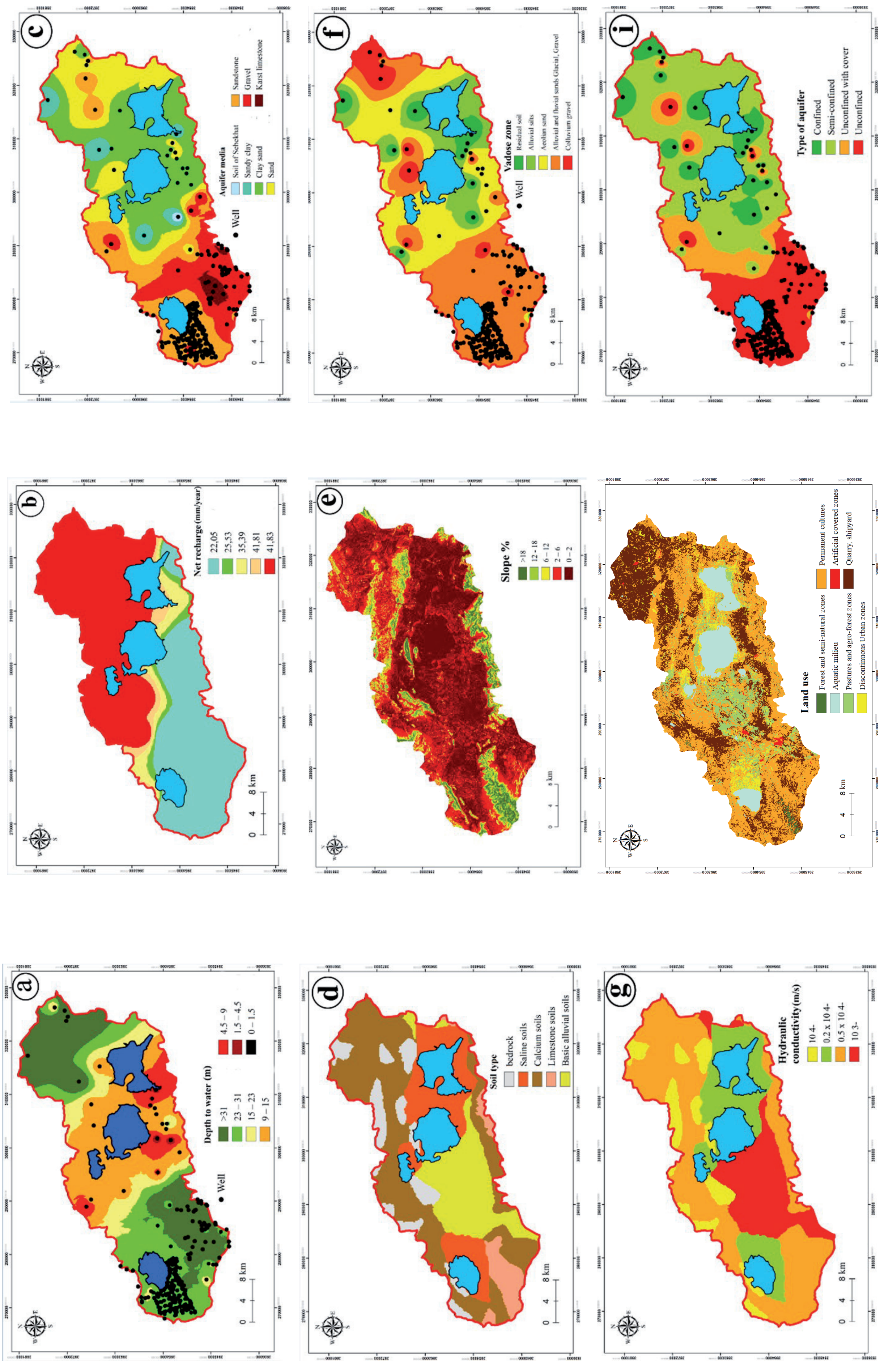

Fig. 4. Input parameters used in groundwater vulnerability mapping:(a) Groundwater depth, (b) Net recharge, (c) Aquifer lithology, (d) Soil types, (c) Topography, (f) Impact of vadose zone, (g) Hydraulic conductivity, (h) Land use, and (i) Type of aquifer.

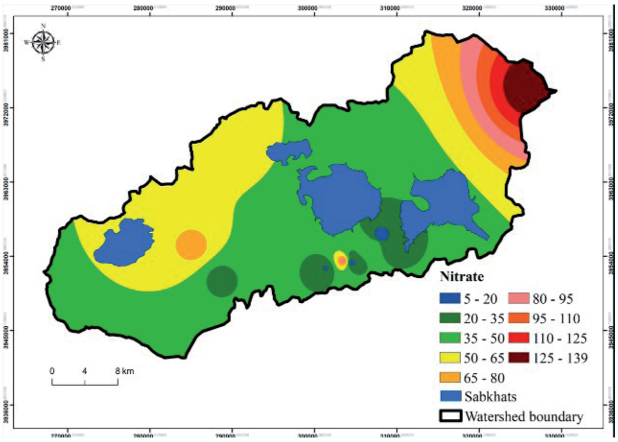

Fig. 5. The nitrate concentration map.

SINTACS method provided relative results and could serve as a complementary method to DRASTIC and SI. However, the GOD model appears less suitable as it shows a weaker correlation with nitrate pollution patterns.

It should be noted that the choice of the most appropriate method for vulnerability assessment method may vary, particularly considering the specific contaminants of concern, the extent and quality of the data available, and the resources available for data collection and analysis. Therefore, in some situations, a combination of methods or a method tailored to local conditions may be necessary to derive the most comprehensive and accurate appraisal of groundwater vulnerability.

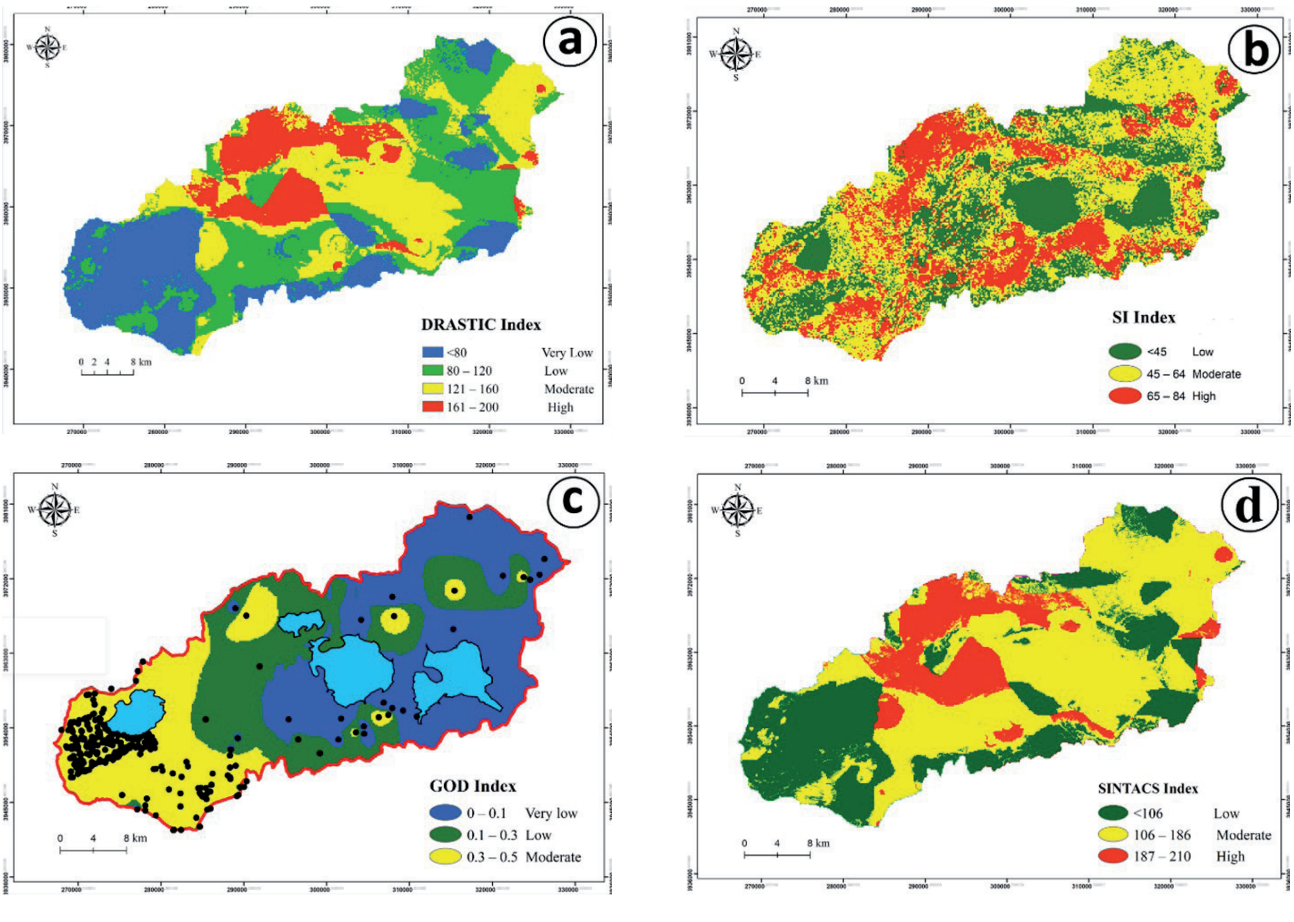

Fig. 6. Vulnerability maps of the Ank Djamel watershed aquifer according to the (a) DRASTIC, (b) SI, (c) GOD, and (d) SINTACS.

north-central regions. Areas of high risk (17%) are predominantly concentrated in the central-northern part of the basin.

Based on the comparison with the spatial nitrate distribution map, which serves as a validation data set, and the results of applying both the DRASTIC and SI methods, they appear to be the most suitable for assessing groundwater vulnerability in the studied area. Both methods identified areas at high risk from agricultural activities with high nitrate levels. The

Conclusions

This study is the first attempt to delineate the groundwater vulnerability to pollution in the Ank Djamel basin, located in northeastern of Algeria. this semi-arid region is characterized by strong agricultural activity, where groundwater plays a crucial role whether for drinking water supply or irrigation. For this objective, four methods were used for a comparative assessment, namely DRASTIC, SINTAC, GOD, and SI. All relevant data layers were prepared and analyzed using a GIS environment to assess the basin's vulnerability.

Vulnerability indices obtained from these models identified four classes of vulnerability for the DRASTIC model, ranging from very low to high, with high vulnerability zones covering 16.68% of the area. The SI and SINTACS models show three classes of vulnerability: low, medium, and high, with high vulnerability areas covering 34.37% and 17% of the study area, respectively. The GOD method identified three vulnerability classes: very low, low, and moderate, with no high vulnerability class. Intrinsic vulnerability models, such as DRASTIC and SINTACS, exhibit similarities in their vulnerability assessments due to their use of a common set of parameters.

The northern and central regions of the study area exhibit high groundwater vulnerability. This susceptibility to contamination is largely due to the shallow depth of the water table and the high hydraulic conductivity.

DRASTIC and SI methods were found to be the most suitable for assessing groundwater vulnerability in this study area, due to their strong correlation with high nitrate concentrations from agricultural activities. The SINTACS method also provided relevant results and can be used as a complementary approach. The GOD method, while informative, appeared less effective in this context. Future assessments should consider a combination of methods or tailor methods to local conditions to achieve the most comprehensive and accurate assessment of groundwater vulnerability.

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Conflict of Interest

The authors declare no conflict of interest.

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