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Research Article

Vulnerability assessment in fractured aquifer using improved vulnerability index: Applied to Gabes aquifer, Southeastern Tunisia

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Abstract: The Gabes aquifer system, located in southeastern Tunisia, is a crucial resource for supporting local socio-economic activities. Due to its dual porosity structure, is particularly vulnerable to pollution. This study aims to develop a hybrid model that combines the Fracture Aquifer Index (FAI) with the conventional GOD (Groundwater occurrence, Overall lithology, Depth to water table) method, to assess groundwater vulnerability in fractured aquifer. To develop the hybrid model, the classical GOD method was integrated with FAI to produce a single composite index. Each parameter within both GOD and FAI was scored, and a final index was calculated to delineate vulnerable areas. The results show that the study area can be classified into four vulnerability levels: Very low, low, moderate, and high, indicating that approximately 8% of the area exhibits very low vulnerability, 29% has low vulnerability, 25% falls into the moderate category, and 38% is considered highly vulnerable. The FAI-GOD model further incorporates fracture network characteristics. This refinement reduces the classification to three vulnerability classes: Low, medium, and high. The outcomes demonstrate that 46% of the area is highly vulnerable due to a dense concentration of fractures, while 17% represents an intermediate zone characterized by either shallow or deeper fractures. In contrast, 37% corresponds to areas with lightly fractured rock, where the impact on vulnerability is minimal. Multivariate statistical analysis was employed using Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA) on 24 samples across six variables. The first three components account for over 76% of the total variance, reinforcing the significance of fracture dynamics in classifying vulnerability levels. The FAI-GOD model removes the very-low-vulnerability class and expands the spatial extent of low- and high-vulnerability zones, reflecting the dominant influence of fracture networks on aquifer sensitivity. While both indices use a five-class system, FAI-GOD redistributes vulnerability by eliminating very-low-vulnerability areas and amplifying low/high categories, highlighting the critical role of fractures. A strong correlation (R^2 = 0.94) between the GOD and FAI-GOD indices, demonstrated through second-order polynomial regression, confirms the robustness of the FAI-GOD model in accurately predicting vulnerability to pollution. This model provides a useful framework for assessing the vulnerability of complex aquifers and serves as a decision-making tool for groundwater managers in similar areas.

Keywords: Groundwater; Aquifer vulnerability; Fractured media; FAI-GOD index; GOD index; GIS

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Introduction

Groundwater is a vital resource for domestic, agricultural and industrial purposes, especially in arid areas where surface water is scarce and groundwater is the primary source of life and economic prosperity. Global water demand is increasing rapidly due to agricultural, industrial, and domestic needs (Das et al. 2023; Khatri and Tyagi, 2015; Rao et al.

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2021). Forecasts indicate a significant increase in groundwater demand in the coming years (MacDonald et al. 2019), making it necessary to protect this resource, especially in the face of climate change and rapid global population growth.

The dependence of agriculture, in arid and semi-arid, areas on irrigation occupies a special place in discussions of water scarcity and water management, as it consumes more than 70% of the world's total water resources and up to 90% in some developing countries (Prinz et al. 2002). Various studies have shown that excessive pumping, fertilizers and pesticides, industrial effluent discharges, uncontrolled urban landfills, and other anthropogenic activities are the main sources of groundwater pollution (Singh et al. 2015). The sources of groundwater pollution vary depending on natural and human activities, but the overuse of fertilizers in agricultural communities and urban waste are considered the most important factors threatening water quality (Hoque, 2009).

Therefore, a reliable understanding of water quality is necessary to ensure the sustainable management of water resources. Nowadays, vulnerability assessment is necessary as groundwater is often exposed to natural and anthropogenic sources of pollution, rendering this resource unusable (Atoui and Agoubi, 2022). It is therefore important to keep groundwater safe, protect it from pollution hazards, prevent negative impacts on human health and ensure sustainable development. The vulnerability of aquifers is referred to as the susceptibility of groundwater quality to pollutant inputs, which is influenced by the inherent properties of the aquifer. The groundwater vulnerability assessment takes into account physical factors that influence the natural potential for contaminant infiltration into an aquifer. These factors included soil properties (texture, thickness, and permeability), geological characteristics (thickness of the unsaturated zone, stratigraphy), depth to the water table, hydraulic conductivity, topography, and recharge rates. These factors determine how easily water and pollutants flow through the subsurface.

Groundwater is more protected from pollution than surface water due to its depth and geological shielding; however, fractured aquifers are considered among the most vulnerable to pollution risks (Madane et al. 2020; Adegoke et al. 2024). Fractures in the unsaturated zone facilitate the rapid infiltration of contaminants into the aquifer, making groundwater more vulnerable and sensitive. Therefore, studying the groundwater vulnerability to contamination requires high accuracy in order to secure clean and pure groundwater supplies. A recent literature review highlighted that the lineament density is widely used to assess aquifer vulnerability for fractured media as weighting and indexing method (Adegoke et al. 2024; Sekar et al. 2023). The GOD method (Foster, 1987) is widely used in heterogeneous sedimentary environments and considered as one of the easiest approaches requiring only three parameters related to depth, aquifer type, lithology of the vadose zone and depth to the water table.

The GOD method was developed to evaluate aquifer vulnerability using a limited number of parameters (Shrestha et al. 2017). However, vulnerability assessment methods often face limitations, including the use of fixed ranks and weights for parameters as well as the application of standardized parameter sets across different aquifers (Javadi et al. 2017; Rahmani et al. 2019). To address limitations associated with the use of a fixed number of parameters in vulnerability assessment methods, researchers have developed modified approaches. For instance, the DRMSICEL method (Hao et al. 2017) incorporates additional factors such as aquifer thickness, groundwater exploitation, and land use.

Several studies using the GOD method to assess the vulnerability of aquifers in dual-porosity environments neglect the risks associated with fractures, which can reduce the relevance and accuracy of the results. Assessing the vulnerability of fractured aquifers to pollution, particularly in arid regions, remains a challenge in hydrogeology. Conventional indices, such as the GOD index, although widely used, remain limited by their inability to account for the specific characteristics of fractured aquifers.

In fractured environments, several studies have highlighted the need to incorporate a fracture index to refine vulnerability assessments (Akintorinwa et al. 2020; De Souza et al. 2022; Tsegay et al. 2024; Haidery et al. 2024). The fracture index is based on various parameters, including the thickness and depth of the unsaturated zone affected by fractures, the arrangement and density of lineaments, and the hydraulic conductivity of fractured rocks.

To fill these gaps, the FAI-GOD (Fractured Aquifer Index-GOD) model has been developed. This new index incorporates parameters adapted to fractured aquifers, providing a more accurate and better-suited assessment. This approach represents a breakthrough for the sustainable management and protection of groundwater in sensitive environments.

Methods like FAI-GOD and GIS-based mapping integrate these parameters to produce vulnerability indices and spatial analyses. Under natural conditions, areas with high permeability, shallow water tables, and high recharge rates are more susceptible to contamination, while protective layers and low permeability reduce seepage risks. Groundwater vulnerability evaluation is used to identify the hazard status of the underground water sources, thereby enabling safe and secure management and supporting the development of appropriate protection strategies.

In this context, the present study proposes the development of an index specific to fractured aquifers, integrated with the GOD method, giving rise to the hybrid FAI-GOD model. This model combines a Fractured Aquifer Index (FAI) with the conventional GOD approach in order to better characterize and delimit groundwater vulnerability to pollution based on hydrogeological and remote sensing data. By incorporating parameters adapted to fractured contexts, such as lineament density, the FAI-GOD model offers a more detailed and representative assessment of hydrogeological reality.

This approach represents a major methodological advance for the sustainable management and protection of groundwater resources in fractured environments, which are often highly sensitive to contamination. The main contributions of this work can be summarized as follows: 1) The development of a new scoring system (FAI) dedicated to fracture networks; 2) Its integration into an enriched GOD framework adapted to fractured environments; 3) Its validation using robust statistical tools (PCA, AHC) and regression models, applied to a critical case study: the Gabes aquifer.

1 Study area

The study area is part of Jeffara plain, located in southeastern Tunisia and bounded by the extreme northern fringe of the Sahara (Fig. 1). The southern study area lies near the Gulf of Gabes to the east, which influences it with a Mediterranean climate, and extends toward the Grand Erg Oriental to the west, characterized by a predominantly semi-arid to arid climate. Intra-annual rainfall is extremely low and irregular in time and space, averaging 100 mm·a^{-1} to 250 mm·a^{-1}. Exceptionally, the town of Matmata receives most of the average intra-annual precipitation resulting from orographic effects, with an intra-annual evaporation rate ranging between 1,500 mm to 2,000 mm (Jemai et al. 2022).

The study area exhibits significant topographic variation. It encompasses plains to the east, adjacent to the Gulf of Gabes, which gradually rise towards the west into the Matmata plateau region, characterized by hills and mountains. This topographic contrast influences both hydrogeological processes and fracture network development. The eastern plains are generally flat with low elevations, while the western parts feature higher elevations and more dissected terrain. Overall, the alti-

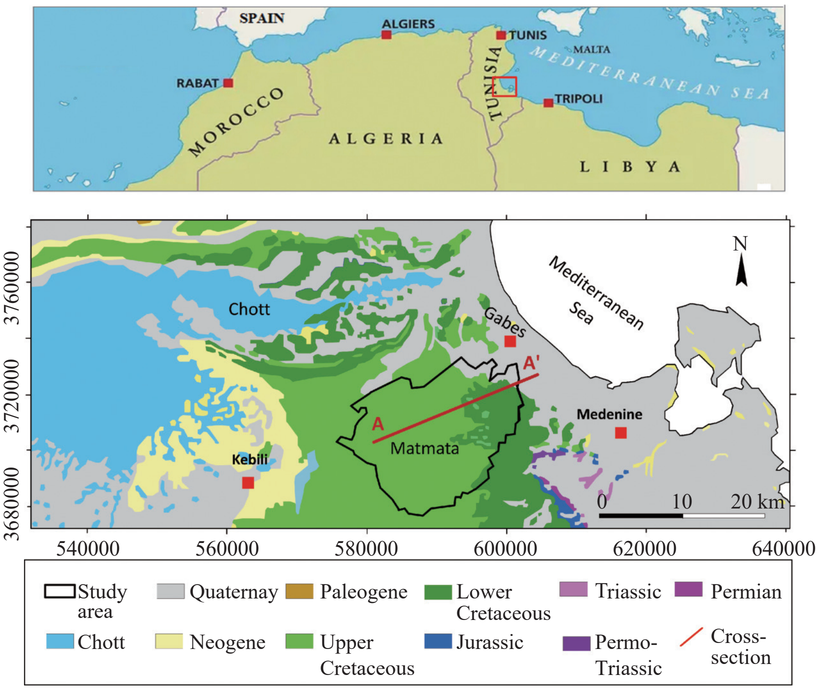

Fig. 1 Location and geological map of the study area (Based on Tunisia geological map 1/500,000)

tude ranges from a minimum of 176 m to a maximum of 602 m, with an average elevation of 398 m.

The stratigraphic layers of southern Gabes stretch from the Permian to the Holocene, however, this paper focuses on the aquifer formations of the multi-layered aquifer system of southern Gabes, which, from bottom to top, include the following units: The Continental Intercalary (CI), the calcareous aquifer of the Coniacian, which is a trapped aquifer, its bedrock is made up of several tens of meters of clayey sediments of Mio-Pliocene age. This bedrock contributes to the superficial aquifer only through sparse conglomerate levels at the Matmata underflow groundwater table, and through the clayey sand over almost the entire area (Fig. 2).

The limestone of the deep Cenomanian, Turonian and Coniacian aquifer is highly karstified, as a result of severe post-tectonic erosion (Ben Hamouda et al. 2013). Its average thickness is about 60 meters, and it outcrops in the highlands of the Matmata region. The study area is characterized by a network of major perpendicularly oriented faults, creating a horst and graben domain, which introduces fragility and shear structures in the hard carbonate rocks. Furthermore, faults play a key role in the collapse and thickening of the main aquifers, which are highly variable and controlled by the faults that have affected them, such that the thickness of the mid-Plio-Quaternary clayey sand exceeds 200 m in the east (Aydi et al. 2022), towards the sea, where it rests unconformably on the thick carbonate Senonian, which dips to the east.

The aquifer in the south of Gabes plays a crucial role as the main water resource for local human activities. However, it is facing serious environmental and anthropogenic challenges. Rising temperatures contribute to increased evapotranspiration, disrupting the region's hydrological cycle. At the same time, the depletion of surface water resources increases the pressure on groundwater, making its management essential to preserve its quantity and quality. Further south, the Matmata carbonate aquifer is subject to excessive exploitation and increasing anthropogenic pressure, compromising its long-term viability (Atoui and Agoubi, 2023). These challenges highlight the importance of sustainable strategies to protect these essential water resources.

2 Material and methods

2.1 Field exploration

The analytical framework of this research is supported by data integrated from 24 distinct sample points. The foundation of the dataset consists of stratigraphic well logs, which offer high-resolution vertical profiles of the subsurface geology. Site-specific depth measurements provide essential geospatial control for correlating these logs across the study area. At a regional scale, remote sensing data, notably satellite imagery, contribute critical information on surface topography, land use, and broader environmental patterns. The convergence, analysis, and visualization of these complementary datasets enable a robust, multi-scale investigation into the geological and environmental processes being investigated.

2.2 Flowchart methodology

The GOD vulnerability index was improved by including the Fracture Aquifer Index (FAI) in order to assess aquifer vulnerability to pollution. The FAI-GOD model is modified following Foster (1987). Nevertheless, indices developed for fractured media have recently emerged to assess aquifer vulnerability to pollution. The methodology adopted in this study is summarized in Fig. 3. The calculation of GOD and FAI-GOD was

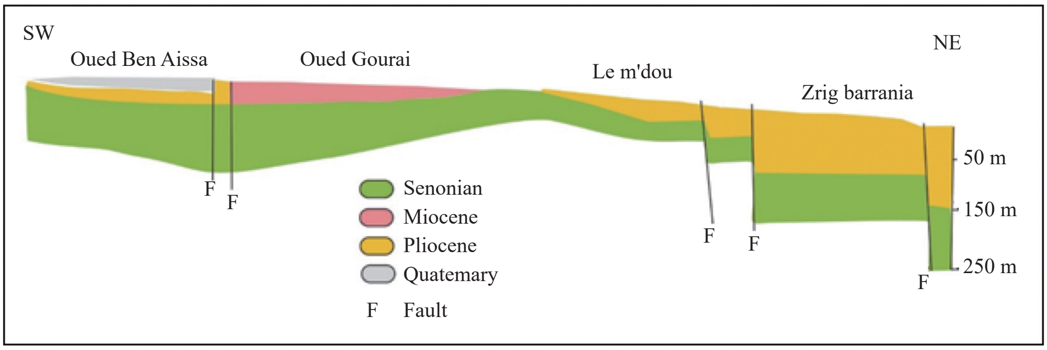

Fig. 2 Geological cross-section A-A' from the study area

computed, compared and discussed in detail below.

2.3 GOD vulnerability index

GOD method was originally developed by Foster (1987). It defines the vulnerability of aquifers based on the resistance to the penetration of pollutants and the attenuation capacity of the layer above the saturated zone. In this approach, the lateral transport of contaminants within the saturated zone is not taken into account. The name of the method is derived from an acronym: i) groundwater occurrence, ii) overlying lithology and iii) depth to the water table.

Compared to practical models such as SEEPAGE, DRASTIC and SINTACS, this model uses-relatively low parameters. This is a simple and quick assessment method for mapping groundwater vulnerability, as classical models assume some general contaminants. It is well suited for areas with limited karstification in carbonate regions. The GOD index (GI), which evaluates the vulnerability of the aquifer to pollution, is obtained by multiplying these three parameters. Each parameter is assigned a score between 0 and 1. The governing equation for the GOD model to calculate the vulnerability index is as follows:

$$GI = G_r \times O_r \times D_r \qquad (1)$$

Where: G_r is the rating assigned to the groundwater occurrence parameter; or is the rating assigned to the overlying lithology parameter; D_r is the rating assigned to the depth to water table parameter.

Groundwater occurrence parameter (G)

This parameter refers to the type of aquifer. Its identification was based on core samples from the boreholes and wells drilled to better understand the aquifer type and material. The rating corresponding to this parameter was obtained according to the notation presented in table 1.

Overlying lithology parameter (O)

The nature of the vadose zone is an important parameter in the assessment of vulnerability, as it affects the speed of propagation of pollutants, and therefore the ability to self-purify against contaminants. It also plays a crucial role in relation with respect to climate change, as it minimizes the rate

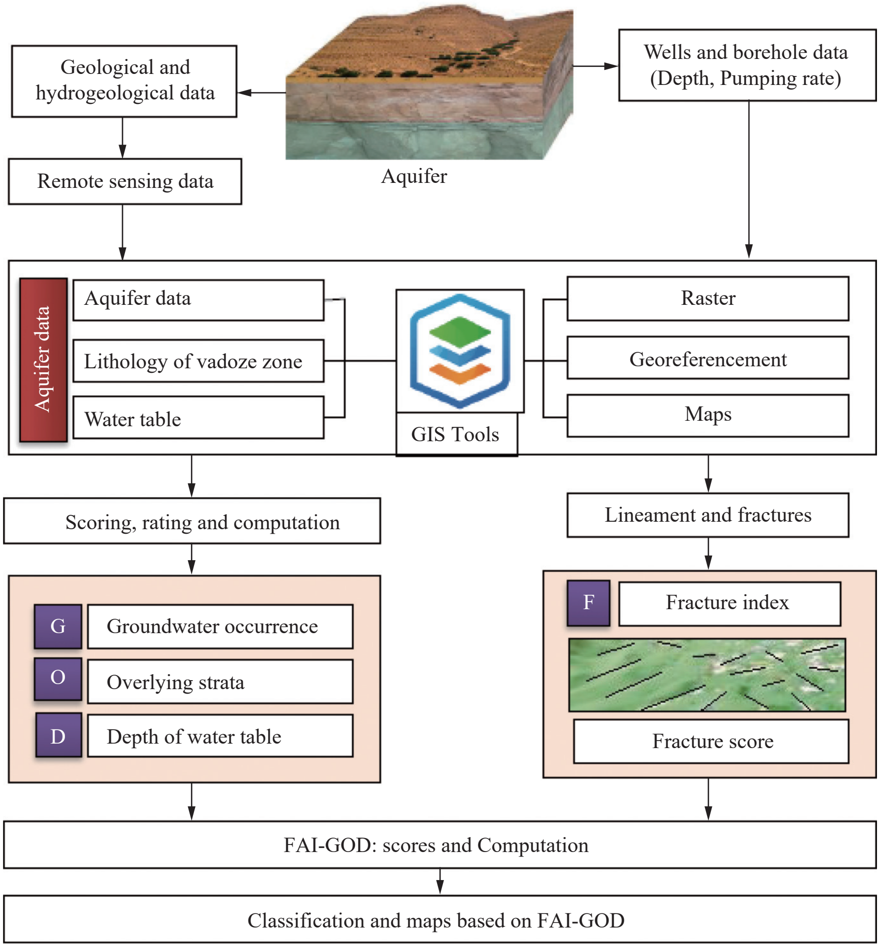

Fig. 3 Flowchart of the improved GOD method and development of the FAI-GOD model

of evaporation. Its impact is determined by the lithology of the ground. The percolation of contaminants to the water table surfaces is all the greater when the lithology is more fragile or loosely consolidated.

The depth to water table parameter (D)

The groundwater depth stands is a critical parameter in vulnerability assessment. When the depth is very high, the contaminant takes longer to reach the piezometric surface. The rating for this parameter was calculated according to Table 1. The ultimate index of the model ranges from zero to 1, respectively. In general, the GOD indices are classified into five different vulnerability categories ranging from "very low" to "extreme" (Table 1). The degree of vulnerability increases with the GOD index (GI). The GOD Index Final Vulnerability Map makes it possible to visualize the main risk areas, which are linked to high indices. To describe this vulnerability, commonly used vulnerability index ranges were used.

Table 1 GOD vulnerability parameters, scores and index classification (Foster, 1987)

G	**Groundwater occurrence**	**Score**
	Confined and artesian	0.1
	Confined	0.2
	Semi-confined	0.3
	Semi-unconfined covered	0.5
	Unconfined	1
O	**Overlying lithology**	**Score**
	Unconsolidated sediments	0.4
	Consolidated porous rocks	0.5
	Aeolian sand	0.6
	Alluvial sands, fluvio-glacial, sand gravels	0.7
	Gravel alluvial	0.8
	Unconsolidated dense rocks	0.9
	Fractured or karstic Consolidate dense rocks	1
D	**Depth to water table (m)**	**Score**
	>100	0.4
	50–100	0.5
	20–50	0.6
	10–20	0.7
	5–10	0.8
	2–5	0.9
	0–2	1
GOD index value		**Vulnerability classes**
GOD index	0–0.1	Very low
	0.1–0.3	Low
	0.3–0.5	Moderate
	0.5–0.7	High
	0.7–1	Extremely high

2.4 Fracture Aquifer Index (FAI)

The fracture index describes the fractures in the layers of the unsaturated zone. Fracture assessment should consider the effect of major faults and fractured geological layers on the relative vertical permeability in the unsaturated zone. Furthermore, according to Krasny (1993) and Lubianetzky et al. (2015), assessing the fracture geometry and characterizing the properties of the fractured rock can be achieved by using the transmissivity (T) due to its association with hydraulic conductivity and fracture aperture. Other studies (Hamza et al. 2017; Aghamelu et al. 2023; Casadiegos-Agudelo et al. 2024) highlight the importance of lineament for assessing fracture networks in dual-porosity aquifers. Typically, lineaments consist of valleys, straight coastlines or hills formed by a series of faults or fractures. These features are often evident on geological or topographical maps and can be highlighted on aerial or satellite photographs. The lineament density is calculated per unit area according to the following relation:

$$\boldsymbol{D} = \frac{(\boldsymbol{V}_1 \times \boldsymbol{L}_1) + (\boldsymbol{V}_2 \times \boldsymbol{L}_2)}{\boldsymbol{S}} \tag{2}$$

Where: D: Line density; L_1 and L_2: Lengths of the lines included in the circle; V_1 and V_2: Values of the population field; S: Area of the circle. The radius corresponds to the search circle used in the "Lineament Density" tool in the GIS software (Fig. 4).

2.5 Incorporation aquifer fractured index and GOD

The importance of fracture zones in their relationship with geological media is critical in protecting groundwater and preventing its pollution. Fractured rock layers are widely ditributed in limestone and calcareous rocks and are highly sensitive to pollution due to human activities. Although fractures differ among rock types, the sensitivity of these layers to pollution depends largely on the geological conditions that generated these fractures. They are highly vulnerable to rainwater seepage and the rapid flow of groundwater, as the flow in fractures dominates, as acts as channels for

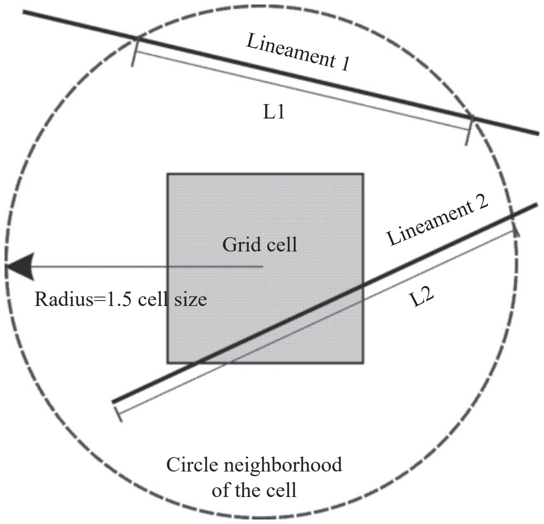

Fig. 4 Lineament density illustration using ArcGIS functions (after Tam et al. 2004)

Table 2 Lineament density values and scores

Factor	Value	Risk to pollution class	Assigned weight to Fracture index
Lineament density (km/km^2)	< 0.5	Low	0.1
	0.5–1	Moderate	0.4
	1–1.5	High	0.8
	> 1.5	Very High	1.0

water flow.

Given the importance of fractures in such groundwater-containing rocks, adopting the fracture factor as a basic element in assessing groundwater vulnerability in fractured rocks is extremely important. Therefore, the degree of fractures and their distribution within rocks were adopted as a basic influencing factor to assess sensitivity to pollution.

Accordingly, the effect of fractures within the matrix, expressed as the fracture score (S_f), was quantified and adopted as a primary factor, while the porous-media factor (Sg) was retained with an assigned weight (Eq. 4).

The coefficient S_g depends on the type of aquifer. If the aquifer is formed by non-fractured sedimentary rocks, S_g has a weight of 1 and fracture score is 0. In this case, the non-modified GOD method is applied to assess vulnerability. In the case of fractured aquifer, a weight of 0.6 is assigned to scores, while the GOD index receives a weight of 0.4 (Table 3). Finally, the third case corresponds to a karst aquifer, in which the maximum score (S_f=0.8) is assigned to the Fractured Aquifer Index (FAI), while only 0.2 is assigned to the GOD index (S_g).

Based on Equation 4 and the weighting scheme

Table 3 Scores adapted to the GOD and FAI index according to aquifer type

Aquifer type	GOD score (S_g)	Fracture score (S_f)
Porous media	1.0	0.0
Fractured rock	0.4	0.6
Karst	0.2	0.8

Table 4 FAI-GOD vulnerability index classification (five classes)

FAI-GOD index	Vulnerability classess
< 0.1	Very low
0.1–0.4	Low
0.4–0.7	Moderate
0.7–1.0	High
>1	Very high

presented in Table 3, the FAI-GOD vulnerability index is classified into five categories, ranging from very low to very high (Table 4).

$$\mathrm{FAI}-\mathrm{GOD}=\mathrm{GOD}^{*}\mathrm{Sg}+\mathrm{F}^{*}\mathrm{Sf} \tag{3}$$

2.6 Validation of the GOD and FAI-GOD model

In the literature, several methods are commonly used to measure the concordance or agreement between two vulnerability maps. Several authors including (Blanchard et al, 2016; Alkaysi et al. 2020) use the Kappa coefficient (K), which is a statistical measure designed to assess the level of agreement beyond what would be expected by chance. Another approach uses correlation coefficients, such as Pearson's correlation coefficient (R), to assess the linear relationship between vulnerability values at corresponding locations on the two maps. A high positive correlation indicates a solid positive link. In addition, the accuracy of one map relative to the other is assessed using the Root Mean Squared Error (RMSE) (Atoui and Agoubi, 2022), and the Mean Absolute Error (MAE), which provide insights into the overall level of agreement. Taken together, these methods help researchers assess the reliability and consistency of vulnerability mapping techniques, leading to a better understanding of vulnerability patterns.

The validation of aquifer vulnerability methods frequently relies on statistical tools such as Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA). PCA is used to reduce dimensionality and identify the most influential variables. The method is based on the diagonalization of the covariance or correlation matrix C, defined as:

$$C = \frac{1}{n-1}\sum_{i=1}^{n}(X_i-\overline{X})(X_i-\overline{X})^T \tag{4}$$

Where: X_i is the vector of observed variables for the i-th sample, and $\overline{X}$ is the mean vector. The eigenvectors of C represent the new principal components, which allow us to understand the variance explained by each dimension. HCA, on the other hand, uses measures of similarity or dissimilarity, often defined by Euclidean distances between observations:

$$d_{ij} = \sqrt{\sum_{k=1}^{p}(x_{ik}-x_{jk})^2} \tag{5}$$

Where: d_{ij} represents the distance between points i and j, and X_{ik} is the value of variable k for point i These distances are then used to construct a dendrogram following aggregation algorithms, such as Ward's method, which minimizes the intra-class variance at each step. Using a combination of these two methods, it is possible to validate the consistency of vulnerability indices by identifying key variables and grouping sites or samples according to similar characteristics. This dual approach guarantees robust validation and reliable interpretation of vulnerability models in complex hydrogeological contexts.

3 Results and discussion

3.1 GOD vulnerability

The GOD parameters have been assessed and scored according to Foster (1987). Each parameter (G, O and D) has been computed and mapped separately and overplaid using ArcMap Raster Algebra 10.8 to produce the GOD map of the study area (Fig. 5). Results highlighted that the study area has been divided into four classes from very low to high vulnerability (Table 5). Conversely, around 8% of the study area had very low vulnerability 29% had low vulnerability, 25% fell within a moderate class, and the high vulnerability class had a percentage around 38%. The very low, low and moderate vulnerability classes (62%) suggest the presence of protective geological features in the study area. Furthermore, the areas with highest vulnerability reflect a low protective layer associated with outcrops of the aquifer strata in the hills

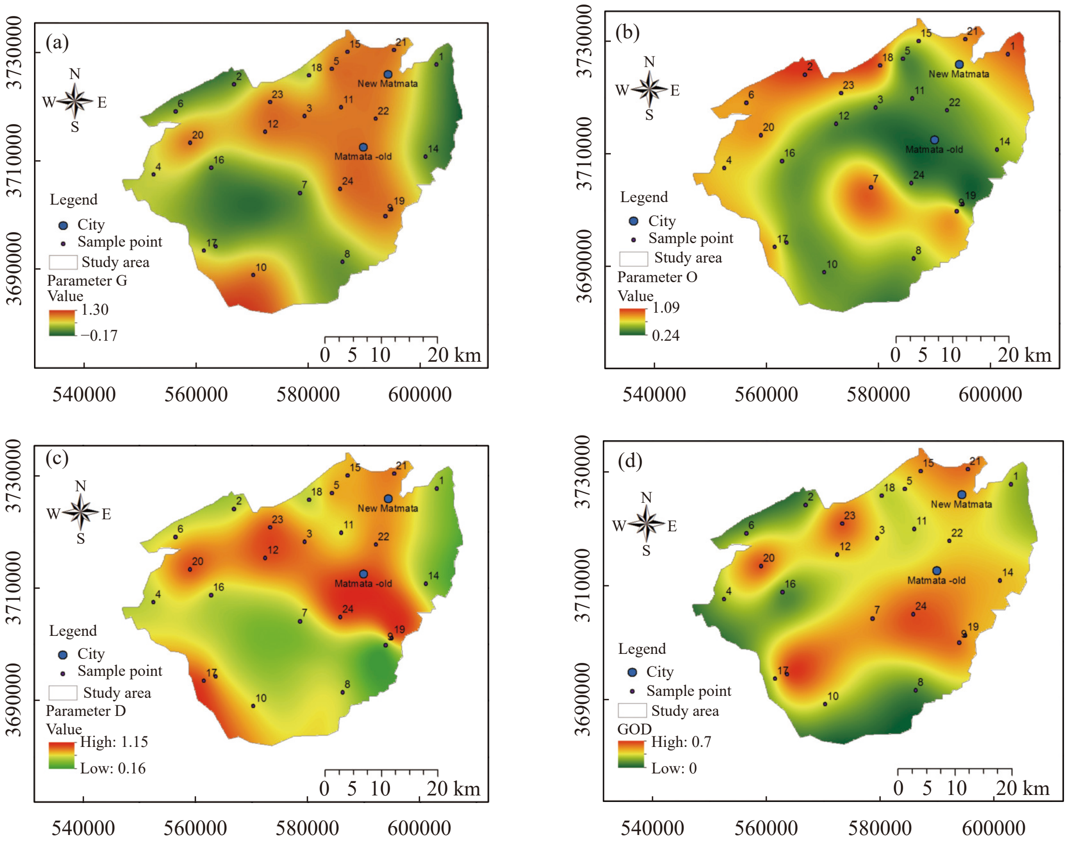

Fig. 5 Parameters and results of the GOD vulnerability assessment in the study area: a) Groundwater occurrence (G), b) Overlying lithology (O), c) Depth to water table (D), (d) Final GOD vulnerability map

Table 5 Results of the GOD vulnerability assessment for the study area

Classes	**Percentage (%)**
Very low	8
Low	29
Moderate	25
High	38
Extremely high	**0**

of the study area and the shallow depth of water table.

The overlying materials factor assesses the types of materials in the vadose zone that can influence the susceptibility of groundwater to contamination. The study area is a fractured aquifer characterized by high hydraulic conductivity and limited self-purification capacity, but the presence of protective materials has influenced the GOD parameters, while the depth to the water table remains a key parameter controlling aquifer protection. The study area exhibited a shallow depth with D values ranging between 0.8 and 1, signifying a high vulnerability to contamination.

Overall, the GI reveals significant spatial heterogeneity in aquifer vulnerability in the study area (Fig. 5). This underlines the importance of taking all three components (G, O, and D) into account in a thorough evaluation of aquifer vulnerability. The GOD method, as illustrated in this study, proves to be a valuable framework for assessing aquifer vulnerability. This method has proved effective in assessing the fragility of local drinking water resources to various threats. The results of the study highlight the spatial variability of vulnerability in the study area, underlining that vulnerability is not uniform across the region. This spatial variability highlights the importance of incorporating geological, hydrological, and aquifer-specific factors into vulnerability assessments.

3.2 FAI-GOD index

The FAI was computed and assessed based on DEM map and lineament density map of study area (Fig. 6a, 6b and 6c). Theses maps were produced using ArcMap 10.8 in order to identify the fracture network in the study area, and consequently the lineament density and FAI were produced. In the second stage, the FAI-GOD index was computed using Map Algebra of ArcGIS 10.8.

It is shown in Fig. 6a that the outcrop of the

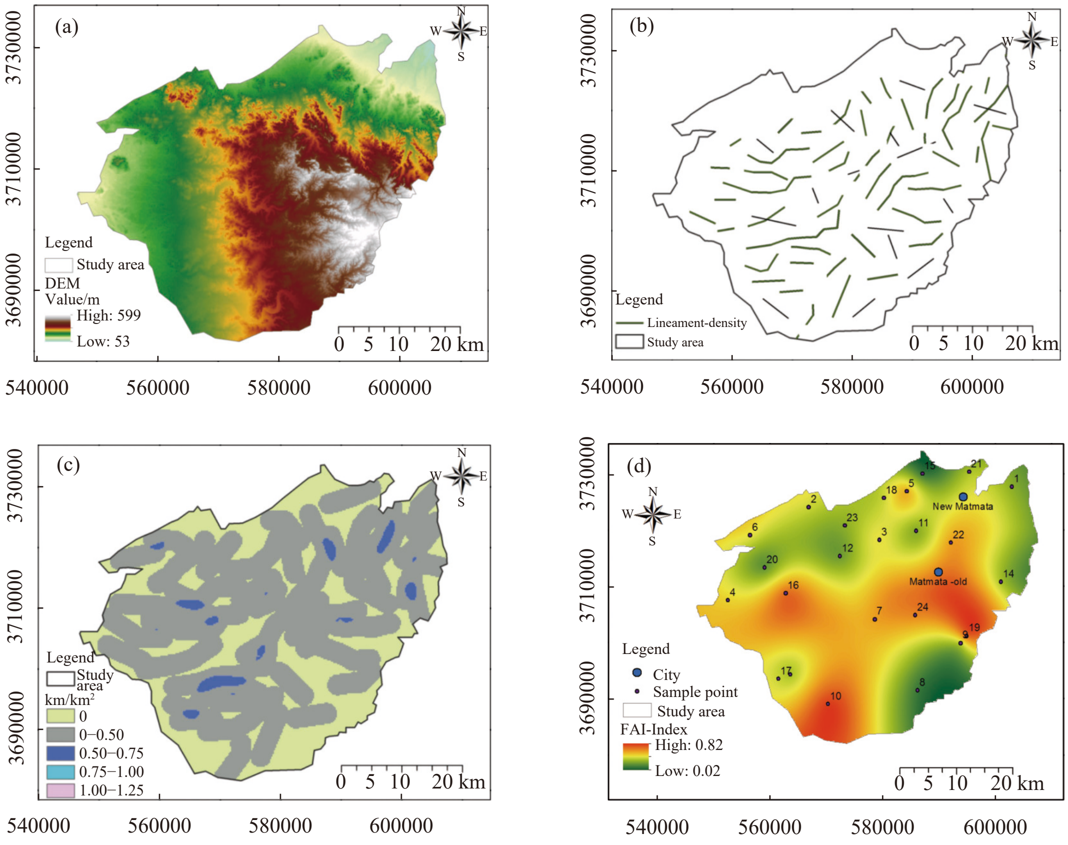

Fig. 6 Derived geospatial maps for the FAI analysis in the study area: (a) Digital Elevation Model (DEM) of the study area, (b) fracture network, (c) Lineament density map, and (d) resulting FAI index map

carbonate aquifer appears in the central eastern part of the study area. This zone is characterized by a highly developed fractures network, which seems the most vulnerable to pollution. The fracture index offers a deeper insight into subsurface geological formations aquifer vulnerability and resource management. Several authors have used multi-class lineament density assessment, such as Piscopo (2001), which has advanced our ability to quantify subsurface heterogeneity and its implications for hydrogeology. The fracture index has profound implications for practical applications in groundwater protection, due to its significant link to groundwater in terms of water storage and mobility, as highlighted by Devi et al. (2001).

The fracture network is well developed in the study area. It is shown in figs. 6.b and 6.c that the fractures were located in the eastern part of study region where mountains and hills occur. Thus, in the northern and western part of the study area, the fractured rock aquifer becomes very deep, and the fractured rocks are covered by sedimentary rocks, therefore reducing their vulnerability. The lineament map, developed based on the fracture distribution in the aquifer, allowed the calculation and spatial mapping of the FAI. Fig. 6d shows that the FAI is strongly correlated with the DEM and fracture network map, indicating that outcropping fractured rocks represent the most vulnerable area to pollution.

The GOD index was coupled with the FAI to assess vulnerability to pollution by introducing fractures parameters into the GOD model. The classification based on the FAI-GOD index identifies three classes, ranging from low to high vulnerability to pollution (Fig. 7), which represents a significant advance in aquifer vulnerability monitoring. This classification highlights the significant influence of lineament density in the study area.

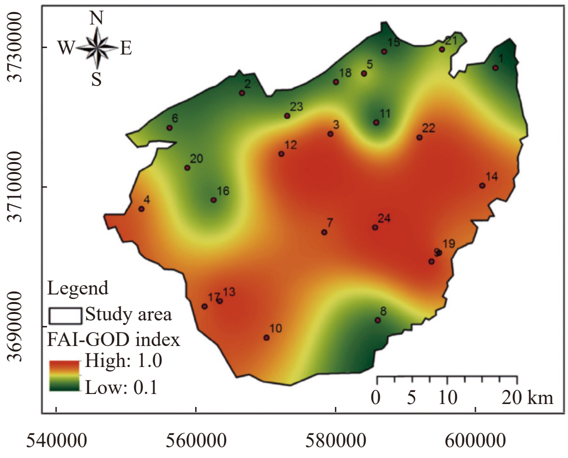

Fig. 7 Spatial distribution maps of the FAI-GOD index and associated vulnerability classes

The FAI-GOD index accounts for the influence of fractures and distinguish three zones of the aquifer. The first zone (46%), the most vulnerable, corresponds to the fractured zone. The second is an intermediate zone (17%) where fractures become deep or less dense, while the third zone (37%) is composed by non-fractured rocks where fractures become very deep and have no direct effect on the vulnerability of the aquifer. The presence of high vulnerability classes, particularly concentrated in areas where lineament density is active, highlights the critical importance of geological fractures and their impact on aquifer vulnerability. These results are consistent with research conducted by (Mendoza and Barmen, 2006; Abdullah et al. 2015; Awawdeh et al. 2020), which highlight the role of lineaments as preferential pathways for contaminants and emphasize their importance in the formation of vulnerability patterns.

3.3 Statistical analysis

To validate groundwater classification based on GOD and FAI index, a multivariate statistical analysis, including both Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA), was carried out to validate the previous results. For HCA and PCA, 24 individuals and 6 variables were analyzed, and the analysis was extended until the first three components explained more than 76% of the total variance. Similarly, HCA was applied using the Euclidean distance between individuals and variables. The results of multivariate statistical analysis are shown in Figs. 8 and 9.

It is noteworthy that the statistical results confirm the classification of groundwater according to their sensitivity to pollution in three classes. Fig. 8 presents the projection of individuals in vector C1×C2, where individuals are grouped into three groups according to the importance of the fracture network in the aquifer. This same result is also confirmed by HCA which also shows three clusters grouping the sampled points according to the Euclidean distance based on the density and importance of fractures in the study area (Fig. 9). The correspondence between the graphical and statistical results suggests the importance of the new method (FAI-GOD index) developed for the assessment of vulnerability to pollution in dual-porosity or fractured aquifers.

The three clusters derived from multivariate statistical analysis PCA (Fig. 8) and HCA (Fig. 9) demonstrate a strong correlation with the actual hydrogeological conditions of the study area. Clus-

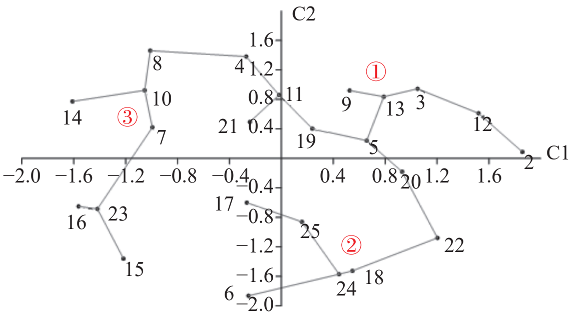

Fig. 8 Projection sampled point on the C1×C2 factorial plane according to the pollution vulnerability indices

Notes: C1 and C2 represent the first and second principal components derived from the PCA analysis, which together explain the largest proportion of variance in the dataset

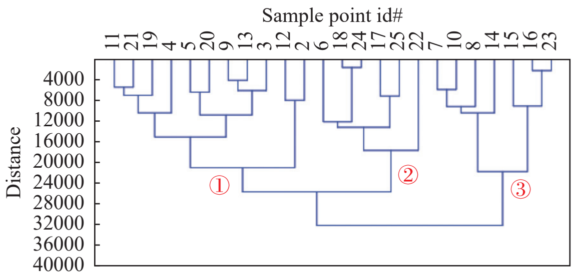

Fig. 9 Hierarchical cluster analysis (HCA) of sampled points based on Euclidean distance derived from FAI-GOD vulnerability scores, revealing three distinct vulnerability groups in the study area

ter 1 corresponds to the outcropping, densely fractured carbonate rocks of the Matmata plateau, confirming their high intrinsic vulnerability. Cluster 3 aligns with the deep aquifer zones in the north of the study area, which are protected by thick clayey sediments, resulting in low vulnerability. The intermediate Cluster 2 represents the transition zone with moderate fracture density and sedimentary cover. Furthermore, the dominance of the first three principal components in the PCA suggests that the overall vulnerability is governed by a few key factors, which we interpret as the fracture influence (PC1) and the intrinsic hydrogeological properties of the aquifer (PC2). This statistical coherence with the known geology validates the physical relevance of the FAI-GOD model. PC3 may explain additional variance related to variations in groundwater occurrence and interactions between the parameters.

3.4 Comparison and validation GOD/FAI-GOD

Comparing the two indices GOD and FAI-GOD shows that the incorporation of the fractured-rock index is very important in assessing aquifer vulnerability to pollution. Therefore, the adoption of the FAI index has showed great importance and has substantially improved vulnerability assessment (Fig. 10). As shown in this study, the identification of vulnerability areas has become more realistic and consistent with the geological characteristics of fractured rocks, while the GOD index assesses vulnerability based solely on intrinsic aquifer parameters. The FAI-GOD index redistributes vulnerability by eliminating the very low class and reducing the moderate class, while amplifying the low and high categories, demonstrating the strong influence of fracture networks on aquifer vulnerability. Hence, the results highlight that this approach aligns with findings from studies such as Mendoza and Barmen, 2006; Abdullah et al. 2015; Hamza et al. 2017; Awawdeh et al. 2020, where authors incorporated fracture networks to improve aquifer vulnerability assessment using DRASTIC and improved FRASTIC.

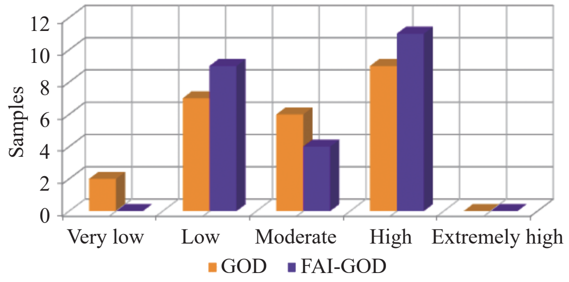

Fig. 10 Comparison between GOD and FAI-GOD methods of aquifer vulnerability assessment in fractured aquifer. The shift toward higher vulnerability classes reflects the impact of fracture-controlled flow

Few studies on the vulnerability of fractured aquifers incorporate lineament density as a key parameter in the calculation of the DRASTIC index. However, works such as those by Mendoza and Barmen (2006), Awawdeh and Jaradat (2010), Abdullah et al. (2015), and Jenifer and Jha (2018) show that adding this parameter can improve the accuracy of the assessment by more clearly identifying areas that are highly vulnerable to pollution. For example, De Souza et al. (2022) studied the region of Caxias do Sul (Brazil) and found that the addition of FAI-index significantly changed the vulnerability classes, whereas the original DRASTIC model showed a different distribution, with a 5% increase in moderate areas, and the appearance of new very high and extreme classes.

The influence of the fracture index is mainly due to its role in controlling groundwater flow velocity and acting as a preferential pathway for contaminants (Sarikhani et al. 2014; Jenifer and Jha, 2018). This parameter is particularly critical in fractured hard rock regions. For instance, Haidery et al. (2024) demonstrated in the Ranchi district (Jharkhand, India), by applying single-parameter sensitivity analysis, that the fracture index, associated with land use and groundwater depth, has a high effective weight in assessing the vulnerability of fractured aquifers. These results confirm that taking the fracture index into account in vulnerability models, such as DRASTIC-LD, improves the sensitivity and reliability of the analyses, thus providing more accurate tools for the management and planning of groundwater resources.

The relationship established between the results of the two indices (GOD and FAI-GOD) is shown in Fig. 11. This relationship shows that a strong second-order polynomial regression exists between the two indices ($R^2 = 0.94$), clearly indicating that this polynomial model can be used to predict vulnerability to pollution in fractured aquifers.

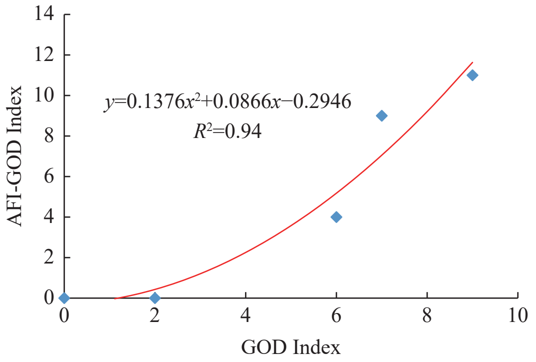

Fig. 11 Polynomial regression of vulnerability assessment indicators AFI-GOD and GOD indices

4 Conclusion

In this study, a Fracture Aquifer Index (FAI) combined with the GOD vulnerability model has been developed to assess groundwater vulnerability to pollution specifically in fractured aquifers. By incorporating the fracturing factor into the GOD method through the FAI-GOD model, this study demonstrates a more precise evaluation of aquifer vulnerability, particularly in complex and heterogeneous fractured aquifer systems.

A robust second-order polynomial regression indicates a strong correlation between GOD and FAI-GOD models ($R^2 = 0.94$), affirming the relevance of this hybrid approach and the reliability of the fracture aquifer index, especially when applied to dual porosity aquifers. This model excels at identifying high-risk zones within dense fracture networks and shallow water tables. The hybrid index stands out as a strategic tool for effective management, monitoring, and protection of groundwater resources. However, it is worth noting that the FAI-GOD model efficacy is somewhat hindered by limitations such as fracture-network data availability and the potential oversimplification of their complexities.

To address these challenges and improve the applicability of the FAI-GOD model, future efforts should focus on integrating hydrodynamic, structural, and fracture network data while considering pollutant mobility. These advances hold great promise for refining vulnerability assessments and supporting more site-specific groundwater protection strategies. The FAI-GOD model is expected to support researchers in advancing conceptual understanding in environmental hydrogeology and can serve as an effective decision-making tool for groundwater management, particularly in similar areas.

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