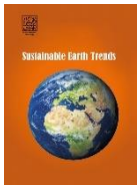
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Comparative performance of DRASTIC and SINTACS models in groundwater vulnerability assessment of the Bam–Narmashir plain: A step toward sustainable aquifer management

Reza Jazini Zadeh[a*]

[a] Department of Environment, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran

ABSTRACT

This study highlights that sustainable groundwater management in arid regions hinges on using vulnerability models to guide protective policies, ensure water security, and advance Sustainable Development Goal (SDG 6) on clean water and sanitation. The research evaluates the vulnerability of the unconfined alluvial aquifer in the Bam–Narmashir Plain, Kerman Province, using two parametric models: DRASTIC and SINTACS. The primary objectives were to compare the performance of these models in identifying pollution-prone zones and to assess the degree of agreement between their outputs and actual groundwater quality data. Seven key parameters were considered: depth to water table, net recharge, soil type, topography, impact of the unsaturated zone, hydraulic conductivity, and lithology. Results indicate that the central and northeastern parts of the aquifer exhibit higher vulnerability due to the high permeability of sediments and shallow groundwater depth. A comparison of the vulnerability maps generated by the two models revealed that the SINTACS model, owing to its greater flexibility in parameter weighting, offers superior discrimination of high-vulnerability zones. Model validation using nitrate concentration data showed that, although both models adequately reflect the general pattern of contamination, their correlation with actual field measurements requires improvement. Overall, the findings underscore the necessity of locally calibrating vulnerability models and implementing continuous groundwater quality monitoring for the sustainable management of water resources in the Bam–Narmashir region.

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*Corresponding author
E-mail address:
r.jazinizadeh@kgut.ac.ir
(R. Jazini Zadeh)

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1. Introduction

In recent decades, rapid population growth, unregulated agricultural expansion, and industrial development have exerted increasing pressure on freshwater resources (Bagheri et al., 2021). This pressure is particularly acute in arid and semi-arid regions such as Iran, where it has led to both quantitative depletion and qualitative degradation of groundwater resources, thereby heightening aquifer vulnerability to anthropogenic contaminants (Khorrami and Malekmohammadi, 2021). Consequences of this trend include reduced infiltration of surface water and precipitation into subsurface layers, declining groundwater tables, and excessive abstraction—all of which directly threaten the sustainability of water resources (Montoya et al., 2023; Pan et al., 2023). In Iran, groundwater serves as the primary source for drinking water, agriculture, and industry (Asghari Moghadam et al., 2017). However, over-extraction has caused severe declines in aquifer levels and reduced the thickness of saturated zones (Kazemi et al., 2022). Moreover, infiltration of pollutants from industrial, agricultural, and urban activities has increasingly compromised groundwater quality, further underscoring the need for accurate aquifer vulnerability assessments (Salehi et al., 2022; Zardosht et al., 2023). Aquifer vulnerability is defined as the susceptibility of an aquifer to contaminant infiltration and its capacity to resist or buffer against such disturbances (Gallopin, 2006).

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Vulnerability assessment involves collecting and integrating physical, hydrogeological, and contaminant transport data from both the saturated and unsaturated zones to distinguish high-risk areas from low-risk ones (Brand and Jax, 2007). Such assessments play a pivotal role not only in water resource management but also in land-use planning, water quality monitoring, and pollution prevention. In this context, the parametric models DRASTIC and SINTACS both compatible with Geographic Information Systems (GIS) have been widely employed in numerous national and international studies. The DRASTIC model generates a numerical vulnerability index based on seven key parameters: depth to water table, net recharge, aquifer media, soil type, topography, impact of the unsaturated zone, and hydraulic conductivity (Smida et al., 2023). In contrast, the SINTACS model, while structurally similar, offers greater flexibility in parameter weighting, enabling better adaptation to local conditions (Idir et al., 2025). Numerous studies in Iran and abroad have applied these two models to evaluate aquifer vulnerability. For instance, Aneesh et al. (2022) used the DRASTIC model to assess vulnerability in an urban coastal aquifer in India, concluding that over 3.8 million people are at risk of contamination. In Iran, Nadiri et al. (2019) combined DRASTIC and SINTACS in the Khoy Plain and achieved higher correlation with nitrate data, demonstrating that integrated approaches outperform individual models. Similarly, Faal Aghdam et al. (2017) evaluated the Billourdi Plain in East Azerbaijan and found that SINTACS provided more precise delineation of high-vulnerability zones compared to DRASTIC. A study assessed groundwater vulnerability in the Nea Moudania aquifer (Greece) using three GIS-based modified models: Pesticide DRASTIC-LU, Nitrate SINTACS-LU, and Nitrate NV index. The southern and southwestern areas showed the highest vulnerability, with land use and topography identified as the most influential parameters (Kirlas et al., 2023). Furthermore, studies such as Zendehbad et al. (2019) in Mashhad, using nitrate isotopic analysis, identified urban land use and inadequate wastewater infrastructure as the primary pollution sources highlighting the critical importance of detailed vulnerability mapping in urban and agricultural settings. Likewise, Karimi et al. (2023) and Jafarzadeh et al. (2022) emphasized the role of human activities in exacerbating groundwater contamination. Given this context, the present study aims to comparatively evaluate the performance of the DRASTIC and SINTACS models in assessing the vulnerability of the unconfined alluvial aquifer of Bam–Narmashir in southeastern Iran. In line with sustainable water resources management, the findings of this study underscore the need for intelligent and adaptive tools in aquifer vulnerability assessment. Given the increasing pressures from agriculture, water scarcity, and groundwater quality degradation in arid regions such as Bam–Narmashir, sustainable groundwater management requires the integration of hydrogeological knowledge, continuous water quality monitoring, and planning based on locally calibrated vulnerability maps. Employing flexible models like DRASTIC and SINTACS with weights adjusted to local conditions not only enhances the accuracy of identifying sensitive zones but also supports informed decision-making for groundwater protection, pollution risk reduction, and ensuring equitable, long-term water access for future generations principles central to Sustainable Development Goal 6 (SDG 6).

This aquifer is the main source of water for regional agricultural activities and, due to its high permeability, is particularly susceptible to contamination from anthropogenic land uses. A precise vulnerability assessment of this aquifer can support the development of effective management strategies, targeted water quality monitoring, and long-term protection of the region's groundwater resources.

2. Material and methods

2.1. Study area

The Bam–Narmashir aquifer is located in the southeastern part of Kerman Province, along the northern margin of the Lut Desert (Dasht-e Lut). It lies approximately 207 km from the provincial capital and spans geographical coordinates between 57°15′ and 59°30′ east longitude and 28°30′ to 29°45′ north latitude. Bounded to the north by the Lut Desert, to the east by the Sistan Desert, and to the west by the Barz mountain range, the aquifer covers an area of about 9,696 km², with a mean elevation of 960 m above sea level. This makes it one of the most significant and

strategic groundwater basins in Kerman Province. The region experiences a hyper-arid desert climate, characterized by extremely hot, dry summers and cold, low-precipitation winters. Annual average rainfall is less than 60 mm, reflecting the severity of aridity and the water scarcity. Despite these harsh climatic conditions, the Bam–Narmashir aquifer plays a vital role in supplying water for agricultural, industrial, and domestic uses, thereby contributing critically to regional development (Iranian Ministry of Energy–Groundwater Resources Department, 2020). Given its hydrological and socio-economic importance, the aquifer has attracted considerable attention from researchers and water management authorities, particularly in studies related to groundwater resource management, vulnerability assessment of subsurface water tables, and strategic planning for sustainable agricultural development in southeastern Iran. The geographic location of the aquifer is shown in Fig. 1.

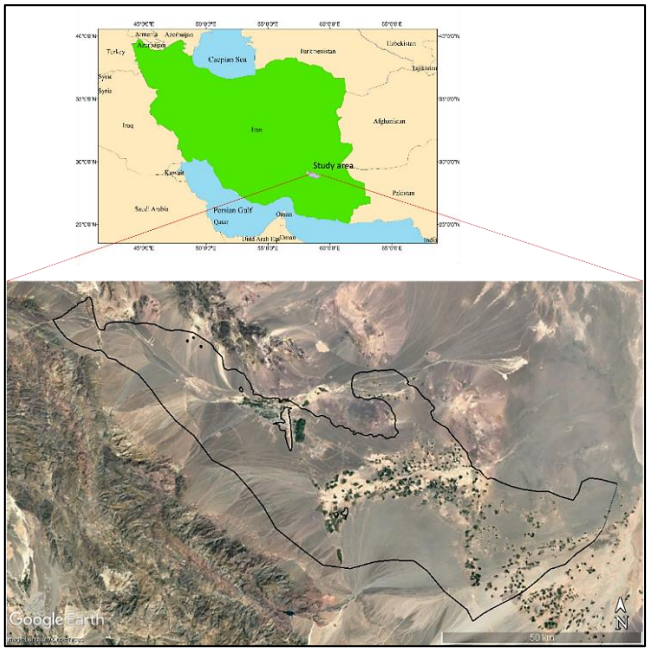


Fig. 1. Location of the Bam–Narmashir aquifer in Google Earth.

In this study, the long-term groundwater data used in this study were provided by the Regional Water Company of Kerman, Iran. The vulnerability of groundwater resources in the Bam–Narmashir Plain was assessed using two well-established and operational models: DRASTIC and SINTACS. These models were selected due to their widespread application, adaptability to the region's hydrogeological conditions, and the feasibility of comparing their outputs through standardized vulnerability maps. Both models are based on the integration of multiple parameters that influence contaminant infiltration and transport; however, they differ in scoring schemes, weighting approaches, and flexibility, differences that are detailed below.

3.2. DRASTIC model

The DRASTIC model is one of the most widely used methods for assessing aquifer vulnerability to contamination. It was originally developed by Aller et al. (1987) and is based on seven hydrogeological parameters. Each parameter is assigned a rating (r) and a relative weight (w), which together yield a numerical DRASTIC Index (DI) that reflects the aquifer's vulnerability index. The seven parameters are Eq. 1:

$$DI = Dr \cdot Dw + Rr \cdot Rw + Ar \cdot Aw + Sr \cdot Sw + Tr \cdot Tw + Ir \cdot Iw + Cr \cdot Cw \quad (1)$$

Whereas, D: Depth to water table, R: Net recharge, A: Aquifer media, S: Soil type, T: Topography (slope), I: Impact of the unsaturated zone,C: Hydraulic conductivity.

3.2. SINTACS model

The SINTACS model was developed by Civita and De Regibus (1995), building on earlier work from 1990 for assessing aquifer vulnerability in southern Italy. While it retains

a parameter structure similar to DRASTIC, SINTACS offers greater flexibility in both rating and weighting, allowing the model to be tailored to specific contamination sources (e.g., point-source, diffuse, agricultural, or urban pollution).

The main parameters of the SINTACS model include the following: depth to water table (D), net recharge (R), aquifer media (A), soil type (S), topography (T), characteristics of the unsaturated zone (I), and aquifer hydraulic conductivity (C). The vulnerability index in the SINTACS model is calculated as follows (Eq. 2):

$$I = \sum_{i=1}^{7} (iP * iW) \quad (2)$$

Where (iP) is the rating assigned to each parameter and (iW) is its corresponding weight. This structure allows the model to be dynamically adapted to the specific characteristics of each study area. In this study, both models were implemented within a Geographic Information System (GIS) environment. Spatial layers for each parameter were prepared using field data, geological maps, remote sensing, and hydrogeological surveys. The resulting vulnerability maps were then validated against measured nitrate concentrations in groundwater to evaluate model performance and reliability.

In this study, groundwater vulnerability assessment was conducted using ArcGIS 10.8, which was employed for all spatial analyses, layer integration, and vulnerability mapping—consistent with standard practices in Iranian hydrogeological research. The analysis was performed at a spatial resolution of 30 meters, based on SRTM DEMs and Landsat-derived land use data, supplemented by geological, soil, and land use vector layers at scales of 1:25,000 to 1:100,000. In high-priority zones, higher-resolution inputs (e.g., 10 m Sentinel-1 imagery for land use) were incorporated where necessary. All modeling, processing, and validation steps have been completed, and the final vulnerability maps were successfully generated and evaluated.

3. Results and discussion

3.1. The spatial of each individual parameter

Before implementing the DRASTIC and SINTACS models, all spatial data layers corresponding to the seven parameters of each model were processed and analyzed using a Geographic Information System (GIS) to gain a more precise understanding of the spatial behavior of factors influencing aquifer vulnerability. To generate continuous and interpretable maps, the Kriging interpolation method was employed, as it effectively models spatial variability from point-based measurements. The spatial distribution of each individual parameter is presented and analyzed below.

3.1.1. Spatial variation of topography

The spatial distribution of slope across the aquifer reveals considerable variability throughout the study area. The western and central parts exhibit relatively gentle slopes, represented by light and dark green tones in Fig. 2-a. These regions are topographically smoother, with limited elevation changes. In contrast, the eastern and northeastern sectors are characterized by moderate to steep slopes, visible as yellow, orange, and red hues. These areas display greater relief and more pronounced elevation differences. This spatial pattern indicates that slope increases toward the east and northeast, while the western and central zones show a more uniform and gentler topographic gradient. Topography significantly influences aquifer vulnerability by controlling surface runoff, infiltration rates, and flow pathways, with flatter or depressional areas typically exhibiting higher vulnerability due to prolonged water residence time and greater potential for contaminant infiltration, whereas steep slopes tend to reduce vulnerability by promoting rapid runoff and limiting percolation.

3.1.2. Spatial variation of the unsaturated zone

The spatial distribution of sediment texture in the unsaturated zone (Fig. 2-b) shows that a large portion of the aquifer consists of fine-grained, clay-dominated deposits. Grain size becomes coarser toward the west and southwest. Along the central belt, areas with medium-grained sediments appear as medium green, whereas the western and southwestern parts are depicted in dark green, indicating coarser deposits that facilitate faster contaminant transport. This spatial pattern reflects significant heterogeneity in unsaturated

zone sediment texture, which is highly relevant for hydrogeological characterization and regional vulnerability assessments.

3.1.3. Spatial variation of hydraulic conductivity

Hydraulic conductivity values range from approximately 1.3 to 10.5 m/day and are displayed in five color classes from yellow to purple (Fig. 2-c). Lower hydraulic conductivity zones (1.3–4.6 m/day) are primarily located in the eastern and northeastern parts of the aquifer, indicating areas with limited permeability. Conversely, the southern and southwestern regions exhibit higher values (up to 10.5 m/day), suggesting the presence of coarser geological units or more active fracturing. This heterogeneous spatial pattern implies that groundwater transmission capacity varies significantly across the aquifer, and high-conductivity zones may play a critical role in both aquifer recharge and contaminant migration.

3.1.4. Spatial variation of saturated zone media

The spatial distribution of saturated zone sediments is shown in Fig. 2-d. Red areas represent fine-grained deposits—typically clay and silt—formed in low-energy depositional environments such as marine basins. Due to their very low permeability, these sediments significantly impede groundwater flow and exhibit minimal contaminant transport potential. Medium green zones indicate slightly coarser sediments with moderate permeability, allowing faster contaminant movement. Finally, blue areas correspond to coarse-grained deposits—often found in alluvial fans or recent alluvia—characterized by sandy to gravelly textures. These highly permeable units promote rapid groundwater flow and thus represent zones of higher vulnerability to contamination.

3.1.5. Spatial variation of depth to water table

Fig. 2-e displays the spatial distribution of groundwater depth. Red zones indicate the shallowest water tables (18–33 m), whereas dark blue areas represent the deepest water tables (up to ~130 m). Regions with shallow groundwater (red and orange) are more vulnerable to contamination due to the shorter travel distance for potential pollutants. In contrast, areas with deep water tables (blue tones) exhibit lower vulnerability because contaminants must traverse a thicker unsaturated zone before reaching the aquifer.

3.1.6. Spatial variation of soil texture

The soil map (Fig. 2-f) distinguishes three soil types, each with distinct physical and hydraulic properties. Light green areas correspond to bare rock or non-soil surfaces, typically composed of dense, unfractured bedrock with very low permeability, thus playing a limited role in contaminant transport. Blue zones covering a large portion of the aquifer represent medium-textured soils containing a mix of fine and coarse particles. These soils exhibit moderate permeability, and their hydrological behavior depends on the relative proportions of clay, silt, and sand; overall, they present a greater potential for contaminant transmission. Red areas indicate fine-textured soils with very low permeability, which retard contaminant movement.

3.1.7. Spatial variation of net recharge

Net recharge is presented spatially in Fig. 2-g (in mm/year). Due to the region's extremely low precipitation, overall recharge rates are minimal. Dark blue areas show the highest recharge rates (14–17.5 mm/year), while very light blue zones indicate the lowest values (0.28–3.29 mm/year). High-recharge zones are generally located in areas with high permeability and favorable slope, which enhance infiltration. Consequently, these areas also present a higher potential for rapid contaminant transport into the aquifer.

3.2. Parameter rating in the DRASTIC model

As part of the DRASTIC model implementation, after preparing and spatially analyzing the relevant data layers, a rating process was carried out to assign a numerical score to each parameter. These ratings were assigned on a scale of 1 to 10, following the standard DRASTIC guidelines while considering the specific hydrogeological conditions of the Bam–Narmashir aquifer. The purpose of this step was to quantify the influence of each parameter on contaminant infiltration and transport, thereby establishing the basis for calculating the final vulnerability index (Tavakoli et al., 2024).

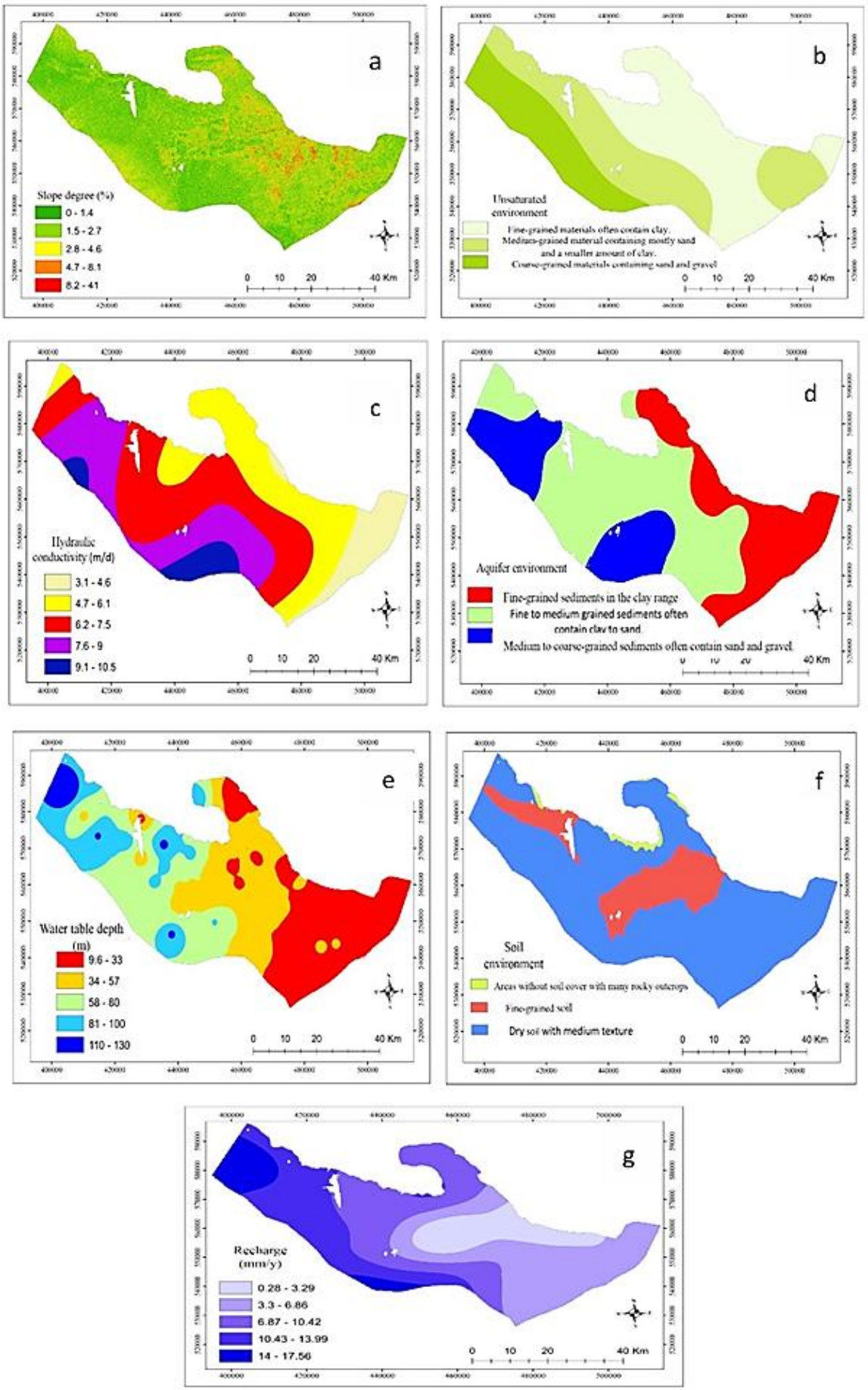


Fig. 2. Spatial distribution of parameters influencing the vulnerability of the Bam–Narmashir aquifer.

3.2.1. Depth to water table

Shallow groundwater zones (18–33 m), due to their proximity to the surface and higher likelihood of exposure to pollutants, received higher ratings (8–9), whereas deeper zones (>80 m) were assigned lower scores (2–5).

3.2.2. Net recharge

Areas with higher infiltration potential and favorable conditions for groundwater replenishment were rated moderately to highly (7–9), while regions with minimal recharge received low ratings (1–3).

3.2.3. Aquifer media

The saturated zone was classified based on sediment texture fine-grained, low-permeability deposits (e.g., clay) received a rating of 1, while coarse, highly permeable sandy and gravelly units were assigned a rating of 9.

3.2.4. Soil texture

Surface soil texture, which controls initial infiltration, was rated up to 7 for moderately permeable soils and as low as 1 for impermeable or compacted soils.

3.2.5. Topography (slope)

Gentle slopes (favoring infiltration over runoff) received higher ratings (up to 6), whereas steep slopes (promoting rapid runoff and reducing infiltration) were assigned lower scores (2–3).

3.2.6. Unsaturated zone

Coarse-grained, highly permeable deposits in the unsaturated zone were placed in higher rating classes (8–9), while fine-grained, low-permeability materials received a rating of 2.

3.2.7. Hydraulic conductivity

Aquifer zones with high hydraulic conductivity indicating greater potential for water and contaminant transport were assigned the maximum rating of 10, whereas low-conductivity zones received scores between 1 and 3.

In addition to rating, each parameter was assigned a relative weight based on its inherent significance in the standard DRASTIC framework: Depth to water table: 5, Net recharge: 4, Aquifer media: 3, Soil Texture: 2, Topography: 1, Impact of the unsaturated zone: 5, Hydraulic conductivity: 3. These weights, combined with the spatially distributed ratings, were used to compute the final DRASTIC vulnerability index and generate classified vulnerability maps for the study area. Detailed rating and weighting criteria for all parameters are provided in Table 1, and the spatially assigned ratings for each parameter are illustrated in Fig. 3 (a–g).

3.3. Parameter rating in the SINTACS model

Given that the DRASTIC model was previously implemented in this study using fixed, standardized weights, the SINTACS model was applied with a more flexible and regionally adapted weighting scheme to enhance accuracy. Unlike DRASTIC which assigns constant weights regardless of pollution source type or local hydrogeological conditions SINTACS allows for dynamic adjustment of parameter weights based on the dominant contaminant sources (e.g., point, diffuse, agricultural, or urban) and site-specific characteristics (Faal Aghdam et al., 2017).

In the Bam–Narmashir aquifer, the primary sources of contamination are diffuse and agricultural in nature, mainly associated with surface-applied agrochemicals and irrigation return flows. Accordingly, greater emphasis was placed on parameters that most strongly influence the vertical transport of contaminants from the land surface to the aquifer particularly depth to water table, net recharge, and hydraulic conductivity.

Relative weights were assigned such that parameters with a higher influence on contaminant migration received greater contribution in the final vulnerability index (see Table 2). For instance, depth to water table and aquifer media were assigned the highest weight of 5, reflecting their critical role in controlling exposure time and transport pathways. In contrast, parameters such as topography and soil type received lower weights, as their influence is comparatively limited under the region's flat terrain and widespread fine-to-medium textured soils (Motlagh et al., 2023).

This adaptive weighting approach represents the key advantage of the SINTACS model over DRASTIC, enabling a more nuanced, context-

sensitive, and realistic assessment of aquifer vulnerability. The spatially distributed ratings for each SINTACS parameter are illustrated in Fig. 4 (a–g).

3.4. Groundwater vulnerability assessment of the Bam–Narmashir aquifer using final DRASTIC and SINTACS maps

Following the parameter rating and weighting procedures, the final vulnerability maps generated by the DRASTIC and SINTACS models were produced and analyzed. These maps integrate spatially distributed parameter ratings and assigned weights to depict the final vulnerability index across the study area.

Table 1. Rating and weighting of parameters used in the DRASTIC model.

Parameter	Weight	Range of Values	Rating
Slope (%)	1	0 – 1.4	2
		1.5 – 2.7	3
		2.8 – 4.6	4
		4.7 – 8.1	5
		> 8.1	6
Soil Texture	2	Bare rock / no soil cover with extensive outcrops	1
		Fine-textured soil	3
		Dry soil with medium texture	7
Aquifer Media	3	Fine-grained deposits (clay-dominated)	1
		Fine- to medium-grained deposits (clay to sand)	5
		Medium- to coarse-grained deposits (sand and gravel)	9
Net Recharge (mm/year)	4	0.28 – 3.29	1
		3.30 – 6.86	3
		6.87 – 10.42	5
		10.43 – 13.99	7
		14.00 – 17.56	9
Depth to Water Table (m)	5	9.6 – 33	2
		34 – 57	3
		58 – 80	5
		81 – 100	7
		110 – 130	9
Hydraulic Conductivity (m/day)	3	3.1 – 4.6	2
		4.7 – 6.1	5
		6.2 – 7.5	8
		7.6 – 9.0	9
		9.1 – 10.5	10
Unsaturated Zone	5	Fine-grained materials (mainly clay)	2
		Medium-grained materials (sand with minor clay)	5
		Coarse-grained materials (gravel and sand)	9

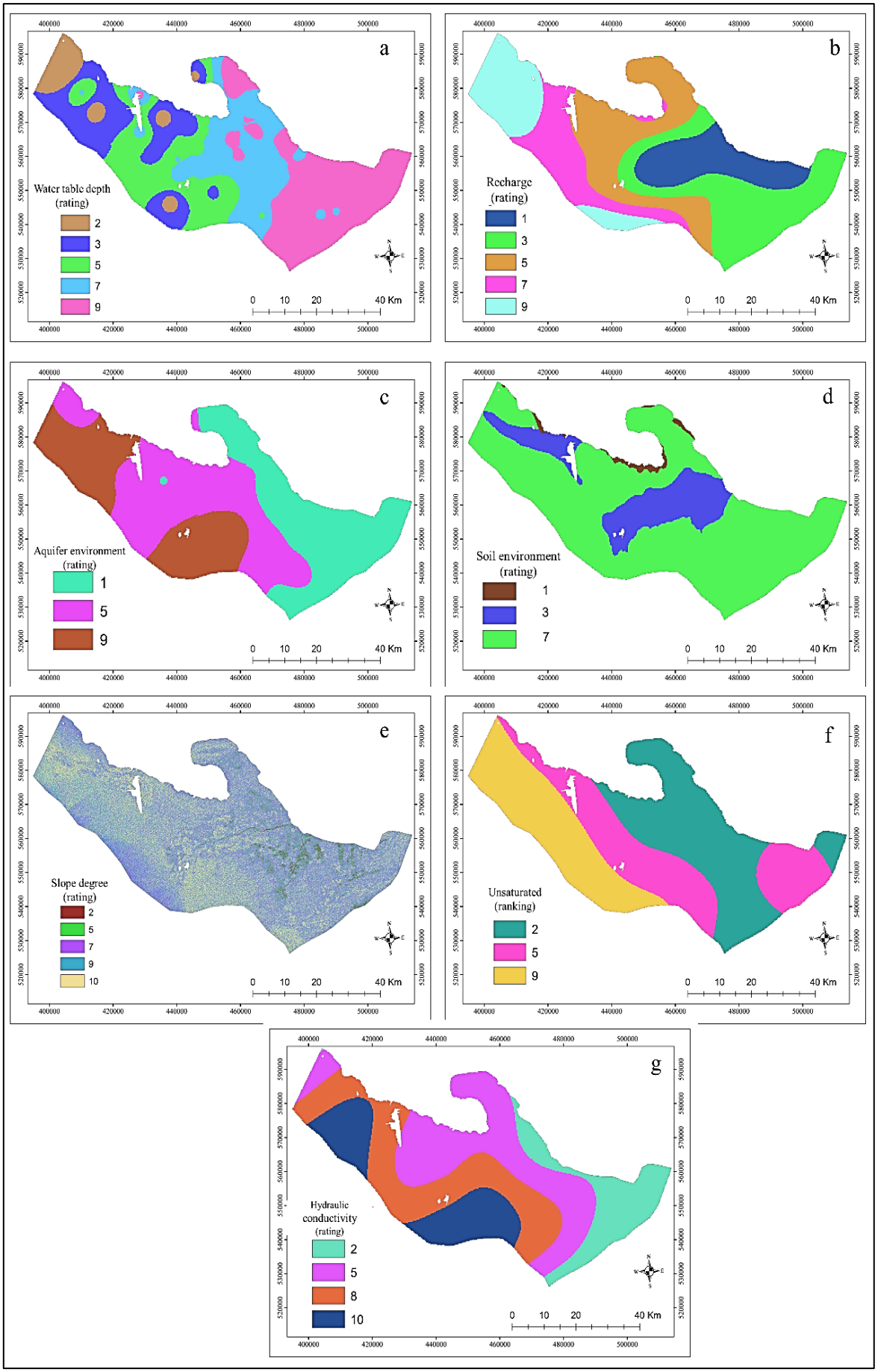


Fig. 3. Rating maps of the parameters used in the DRASTIC model.

Table 2. Rating and weighting of parameters used in the SINTACS model.

Parameter	Weight	Range of Values	Rating
Slope (%)	3	0 – 1.4	2
		1.5 – 2.5	3
		2.6 – 3.1	4
		3.2 – 4.8	5
		4.9 – 6.2	6
		6.2 – 7.3	7
		7.3 – 8.2	8
		> 8.2	9
Soil Texture	4	Clay and silt	1
		Medium-textured soil	4
		Coarse-textured soil	8
Aquifer Media	5	Fine-grained deposits (clay-dominated)	3
		Fine- to medium-grained deposits (clay to sand)	5
		Medium- to coarse-grained deposits (sand and gravel)	7
		Coarse- to medium-grained deposits	8
Net Recharge (mm/year)	4	0.28 – 2.29	1
		2.30 – 4.86	2
		4.87 – 6.42	3
		6.43 – 8.99	4
		9.00 – 11.56	5
		11.57 – 12.99	6
		13.00 – 15.36	7
		15.37 – 16.50	8
		16.60 – 17.56	9
Depth to Water Table (m)	5	9.6 – 20	1
		21 – 37	2
		38 – 50	3
		51 – 65	4
		66 – 78	5
		79 – 87	6
		88 – 100	7
		101 – 115	8

Fig. 5-a presents the final DRASTIC vulnerability map, which classifies aquifer vulnerability into categories ranging from very low to very high, based on the model's standard, fixed weighting scheme. In contrast, Fig. 5-b displays the output of the SINTACS model, which employs a regionally adapted, flexible weighting approach tailored to the dominant pollution sources (primarily diffuse agricultural contamination) and local hydrogeological conditions. As a result, the SINTACS map provides a more refined and

spatially detailed representation of high-vulnerability zones (Chamanehpour et al., 2020; Tavakoli et al., 2024). A visual and statistical comparison of the two maps reveals noticeable differences in the spatial pattern of vulnerability. These discrepancies stem primarily from the distinct rating and weighting strategies employed by each model particularly the adaptive weight assignment in SINTACS, which accounts for regional contamination dynamics and aquifer characteristics. Consequently, the SINTACS model demonstrates a higher capacity to accurately identify areas with elevated potential for contaminant infiltration, offering a more realistic and context-sensitive assessment of groundwater vulnerability in the Bam–Narmashir aquifer.

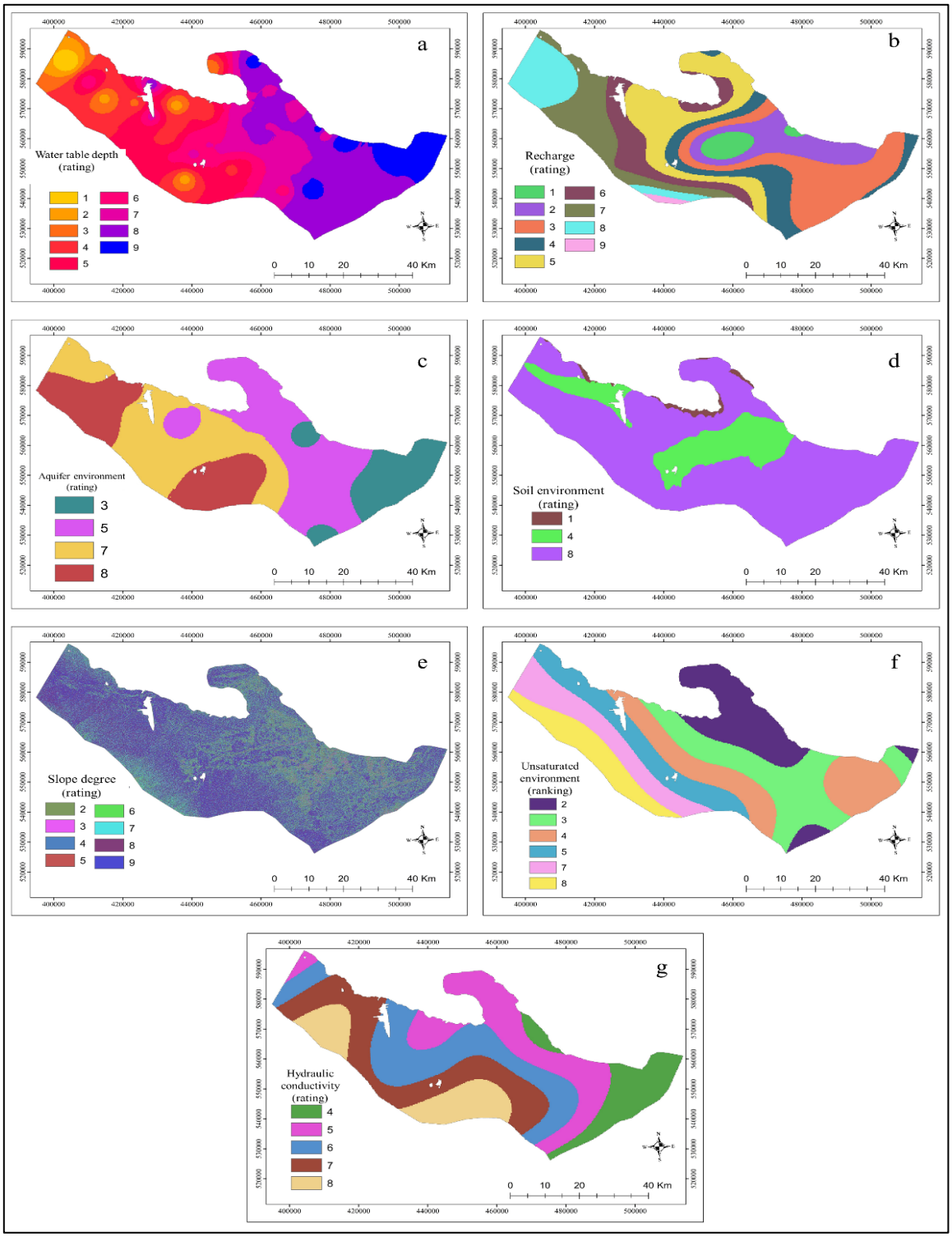


Fig. 4. Rating maps of the parameters used in the SINTACS model.

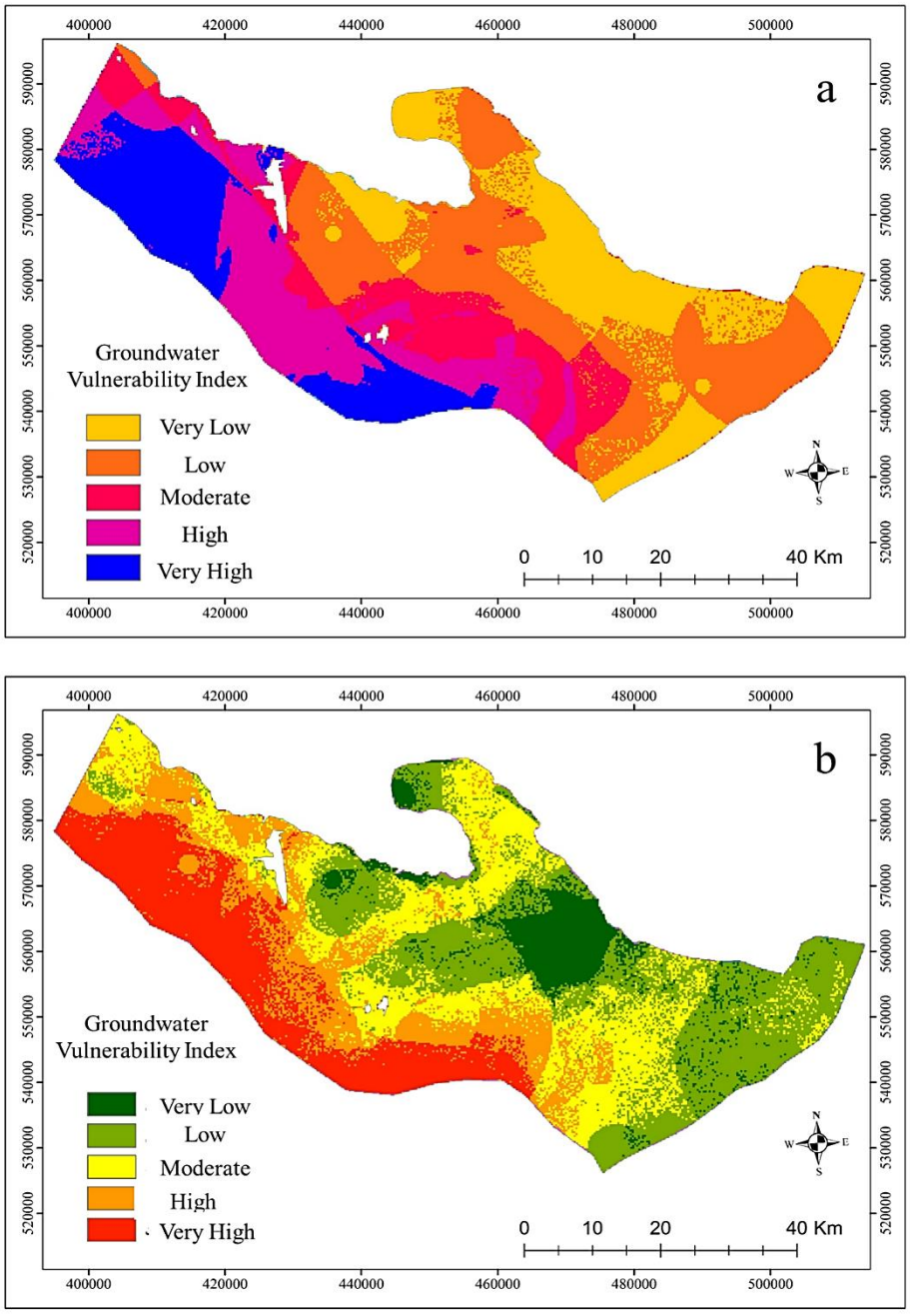


Fig. 5. Final groundwater vulnerability map of the Bam–Narmashir aquifer: (a) DRASTIC, (b) SINTACS.

3.5. Model validation

To validate the DRASTIC and SINTACS models, measured nitrate concentrations from monitoring and production wells across the Bam–Narmashir plain were used as independent indicators of actual groundwater contamination. Nitrate was selected due to its prevalence as a tracer of agricultural and anthropogenic pollution and its relative mobility in the subsurface environment. For each well location, the modeled vulnerability index (DRASTIC or SINTACS score) was compared with the corresponding nitrate concentration (mg/L). Statistical validation was performed using (i) Pearson's correlation coefficient to assess linear association, (ii) ROC curve analysis to evaluate the models' discriminatory power, and (iii) cross-tabulation between vulnerability classes and nitrate-based contamination categories (Chamanehpour et al., 2020). Results indicated that both models successfully captured the general spatial pattern of contamination high-vulnerability zones generally coincided with elevated nitrate levels. However, the statistical

correlation between vulnerability indices and nitrate concentrations was relatively weak (e.g., r<0.5), suggesting limited quantitative accuracy. This discrepancy likely stems from the use of fixed weights in DRASTIC, insufficient spatial density of water quality data, time lags in contaminant transport, and the complex, non-linear nature of pollution processes (Motlagh et al., 2023). These findings highlight the need for local calibration of model weights, enhanced groundwater quality monitoring networks, and the integration of parametric models with machine learning or multivariate statistical techniques to improve predictive reliability. Such refinements are essential for transforming vulnerability maps into actionable tools for groundwater protection and sustainable resource management.

4. Conclusion

The results of this study demonstrate that both DRASTIC and SINTACS are useful parametric tools for assessing aquifer vulnerability to contamination; however, they differ in accuracy and flexibility. Application of these models to the unconfined alluvial aquifer of Bam–Narmashir revealed that, due to the region's specific geological and climatic characteristics including high permeability of alluvial deposits, relatively shallow groundwater depth in parts of the plain, and intensive agricultural activities large portions of the aquifer fall within moderate to high vulnerability categories. A comparative analysis showed that the SINTACS model, owing to its greater flexibility in parameter weighting and its capacity to adapt to local hydrogeological and pollution conditions, provides superior discrimination between high- and low-vulnerability zones. In contrast, while the DRASTIC model offers a simpler and standardized framework, it was less capable of capturing local spatial variations in vulnerability. Model validation against measured nitrate concentrations indicated that although both models correctly represent the general spatial pattern of vulnerability, their correlation with actual groundwater quality data remains relatively weak. This highlights the necessity of local calibration of parameter weights, increased density of water quality monitoring data, and the integration of parametric models with field observations, statistical methods, or artificial intelligence techniques to enhance prediction accuracy and intrinsic vulnerability. Overall, the findings underscore that the Bam–Narmashir aquifer is highly susceptible to contamination due to its intrinsic hydrogeological properties and ongoing anthropogenic pressures. Consequently, integrated groundwater management, continuous water quality monitoring, and the implementation of protection strategies based on vulnerability mapping are urgently needed. High-vulnerability zones in the central plain, coinciding with intensive cultivation, should be prioritized for fertilizer regulation and groundwater monitoring .The SINTACS model particularly when weights are calibrated to reflect local pollution sources and site-specific conditions is recommended as a robust and adaptable approach for supporting decision-making and sustainable groundwater protection in the region.

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