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GROUNDWATER VULNERABILITY AND POLLUTION ASSESSMENT IN AN ARID SAHARAN AQUIFER USING DRASTIC, PIG AND EXPLORATORY SOM ANALYSIS: CASE OF TAIBET (ALGERIAN SAHARA)

SUMMARY

Groundwater represents the primary water resource in the Taibet region, yet its quality is increasingly threatened by expanding anthropogenic activities. This study aims to assess the intrinsic vulnerability and pollution status of the shallow aquifer using the DRASTIC model and the Pollution Index of Groundwater (PIG). The DRASTIC vulnerability map indicates two dominant classes—moderate and high—with the high-vulnerability zone occupying 52.72% of the area. Application of the PIG model to 20 groundwater samples reveals severe degradation, as 95% of samples exhibit PIG values exceeding 2.5, reflecting very high contamination levels. Nitrate concentrations ranging from 21 to 47 mg/L confirm the predominance of anthropogenic pollution, mainly arising from the infiltration of fertilizer-enriched irrigation water and untreated domestic wastewater. A Self-Organizing Map (SOM) analysis was applied to explore the overall consistency between intrinsic groundwater vulnerability and observed contamination patterns based on nitrate concentrations and PIG values. The SOM classification indicates a general consistency between DRASTIC vulnerability patterns and observed contamination indicators, highlighting the relevance of the approach for assessing groundwater vulnerability under arid climatic conditions. Taken together, the results emphasize the urgent need to strengthen groundwater protection measures and to implement integrated and sustainable water management strategies aimed at safeguarding this essential resource over the long term.

Keywords: Taibet, DRASTIC, PIG, contamination, self-organizing map

INTRODUCTION

Groundwater represents a fundamental strategic resource, ensuring a reliable and cost-effective water supply for populations worldwide. In numerous

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areas—particularly in arid and semi-arid environments characterized by limited and highly variable surface water availability—it constitutes the primary source of water for household use, agricultural irrigation, and industrial development. This growing dependence makes groundwater one of the most exploited natural resources globally, with an annual extraction volume estimated at more than 800 km³ (Zektser and Everett, 2004).

Nevertheless, aquifer systems are experiencing increasing stress as a result of demographic growth, the expansion of industrial and agricultural activities, and accelerated urban development. These activities are leading to a gradual decline in groundwater quality, characterized by the accumulation of anthropogenic pollutants such as nitrates, pesticides, and domestic effluents. This situation exacerbates the global water crisis, marked by both the depletion of available resources and the deterioration of their quality.

In Algeria, this issue is particularly critical. Water resources vary considerably across the country: they are relatively renewable in the north but largely non-renewable in the south (Arfa *et al.,* 2022; Bouselsal *et al.,* 2014). In both cases, groundwater quality is declining alarmingly under increasing anthropogenic pressures. Intensive agricultural activities, uncontrolled landfills, and the discharge of untreated wastewater are major sources of contamination, making groundwater protection a key challenge for sustainable development (Houari *et al.*, 2024; Lakhdari *et al.*, 2025; Ouarekh *et al*., 2024).

The Taibet area, situated within an arid climatic setting, represents a clear example of this issue. In this region, groundwater constitutes the main resource for household supply, agricultural irrigation, and socio-economic development. Nevertheless, the growing proliferation of contamination sources, the intensive application of chemical fertilizers, and the discharge of untreated domestic effluents are gradually deteriorating the quality of the shallow aquifer. This growing pressure threatens both the availability of safe water and the long-term sustainability of the resource.

In this context, assessing aquifer vulnerability is essential to anticipate contamination risks and implement appropriate protection measures. Vulnerability assessment makes it possible to identify the most sensitive zones, prioritize management actions, and support the development of sustainable groundwater management strategies.

The primary aim of this research is to evaluate the intrinsic vulnerability of the shallow aquifer in the Taibet region through the application of the DRASTIC model within a GIS environment (Mallik *et al.*, 2021; Novinpour *et al.,* 2022; Lakshminarayanan *et al.,* 2022; Yu *et al.,* 2022). It also aims to validate the results through comparison with the spatial distribution of the Pollution Index of Groundwater (PIG). The outcomes of this work are expected to provide a decision-support tool for local managers and planners, helping them to identify areas at high risk of contamination and to establish effective and sustainable groundwater protection and water security measures.

The contribution of this study lies primarily in the integrated evaluation of intrinsic vulnerability, hydrochemical characteristics, and contamination patterns within a shallow Saharan aquifer strongly influenced by anthropogenic recharge processes.

MATERIAL AND METHODS

Study area

The Taïbet region is located in the northeastern Algerian Sahara and covers approximately 14,622 km² between latitudes 32°14′–33°56′ N and longitudes 6°08′–6°35′ E. Administratively, it includes the municipalities of Taïbet, Bennacer, and El Mnagueur, with an estimated population of about 51,330 inhabitants in 2019. The local economy is mainly based on oasis agriculture and groundwater exploitation, which play a central role in domestic water supply and socio-economic development. The region is characterized by a hot desert climate, where summer temperatures frequently exceed 40 °C, annual rainfall remains below 60 mm, and evaporation reaches nearly 325 mm in July. The landscape is dominated by mobile dunes and sandy plains belonging to the Grand Erg Oriental.

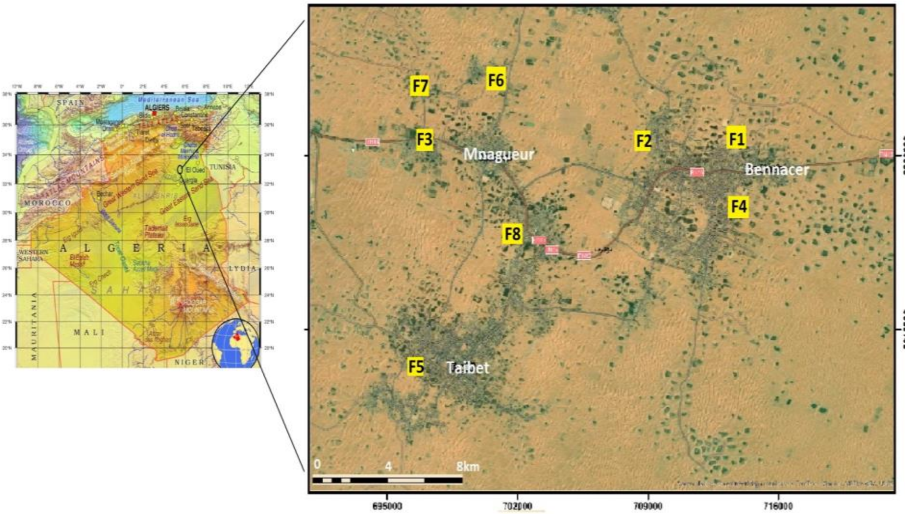

Figure 1. Location of the study area and the boreholes used to determine the lithology of the unsaturated zone

Geologically, the Taïbet region belongs to the Northern Sahara sedimentary basin and is mainly composed of Cretaceous, Tertiary, and Quaternary formations dominated by aeolian sands (Cornet, 1964; Busson, 1967; Castany, 1982). The Quaternary deposits largely cover the older formations and constitute the main geological unit exposed at the surface.

Hydrogeologically, the aquifer system of the region consists, from top to bottom, of three main aquifers: the shallow phreatic aquifer, the Terminal Complex (CT), and the Continental Intercalaire (CI) aquifer (UNESCO, 1972; OSS, 2003, 2010). These aquifers are separated by clayey and evaporitic horizons that ensure partial confinement.

The shallow phreatic aquifer (Fig. 2) develops within Quaternary sandy deposits. Groundwater depth generally ranges from 5 to 20 m depending on topography. Recharge is mainly of anthropogenic origin through irrigation return flows and wastewater infiltration, while natural recharge remains very limited because of the arid climatic conditions (Busson, 1970). Due to its shallow depth, sandy lithology, high permeability, and direct exposure to human activities, this aquifer is highly vulnerable to contamination and constitutes an important water resource for domestic supply and oasis agriculture in the region.

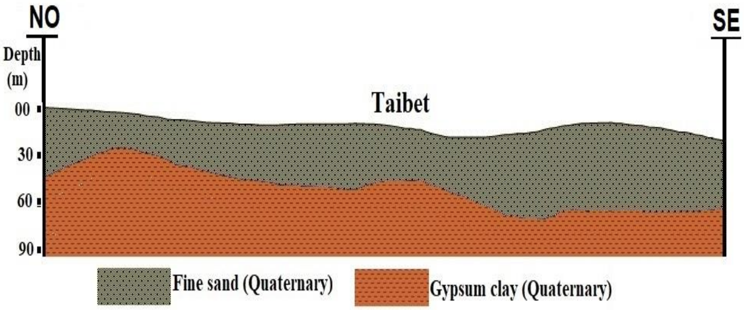

Figure 2. The hydrogeological cross-section shows the phreatic aquifer

Groundwater aquifer vulnerability assessment

Groundwater vulnerability refers to the susceptibility of an aquifer to contamination according to its hydrogeological characteristics (Margat, 1968). Intrinsic vulnerability depends on natural factors such as groundwater depth, soil properties, permeability, and vadose zone characteristics, whereas specific vulnerability also considers the nature and behavior of contaminants. In general, unconfined aquifers are more exposed to pollution because they lack protective confining layers (Bouselsal *et al.*, 2015a).

The DRASTIC model, developed by Aller *et al.*, (1987), is one of the most widely used approaches for assessing intrinsic groundwater vulnerability (Sayed *et al*., 2023; Mallik *et al.*, 2021; Yu *et al.*, 2022). The method evaluates aquifer susceptibility based on hydrogeological parameters controlling contaminant transport from the surface to the saturated zone.

The acronym DRASTIC represents seven key parameters: depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), characteristics of the vadose zone (I), and hydraulic conductivity (C). Each parameter is assigned a rating value between 1 and 10 reflecting its relative influence on contamination potential, together with a weight ranging from 1 to 5 that expresses its importance within the overall model (Fig. 3). The final vulnerability index (ID) is obtained by summing the products of the assigned ratings and their corresponding weights (Eq. 1) (Zhang *et al*., 2021; Satouh *et al.*, 2021).

$$ID = 5Dp + 4Rp + 3Ap + 2Sp + 1Tc + 5Ip + 3Cp \qquad (Eq.\ 1)$$

The vulnerability classification according to the DRASTIC method, as simplified by Engel *et al.*, (1996), is based on grouping the computed vulnerability index into four classes to facilitate interpretation and cartographic representation. In this approach, an index value lower than 100 indicates low vulnerability, values between 100 and 140 correspond to moderate vulnerability, values ranging from 140 to 200 reflect high vulnerability, and values exceeding 200 denote very high vulnerability. The resulting index thus represents the degree of susceptibility of a given hydrogeological unit to potential contamination and serves as an effective decision-support tool for groundwater protection and management.

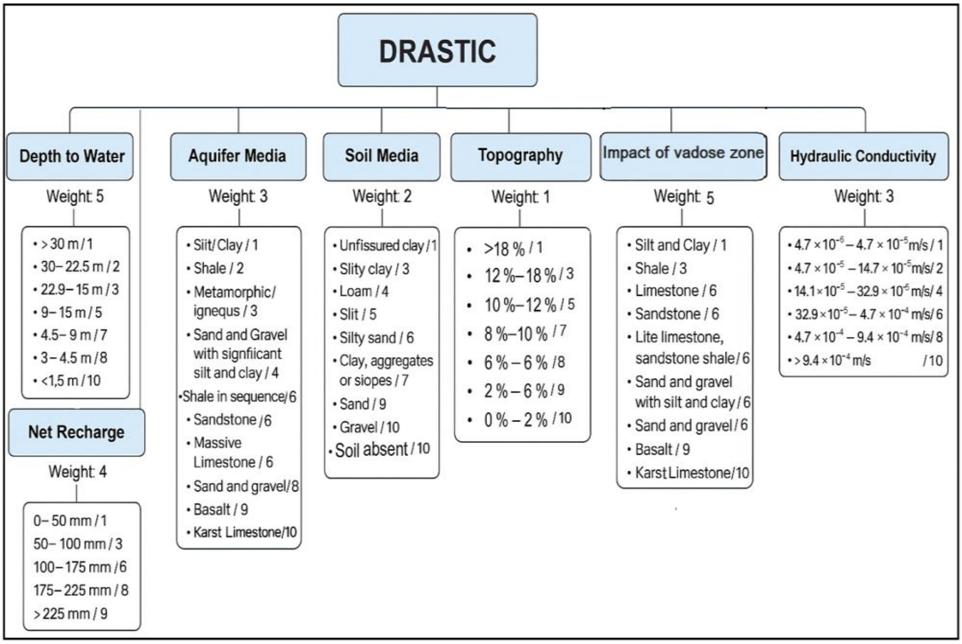

Figure 3. Flowchart illustrating the parameter ratings and corresponding weighting factors applied in the DRASTIC model

This method presents several advantages: it is simple to apply, adaptable to different geological contexts, and allows for the spatial representation of aquifer vulnerability through the use of the GIS. However, it is based on certain simplifying assumptions, notably that contamination originates exclusively from surface sources, that pollutants move in dissolved form, and that transfer occurs vertically (Saravanan *et al.*, 2023; Novinpour *et al.*, 2022; Lakshminarayanan *et al.*, 2022). Despite these limitations, the DRASTIC method remains an effective and well-recognized scientific tool for water resource management planning, the protection of water abstraction points, and the prevention of groundwater pollution risks.

Data Measurement and Preparation

Groundwater vulnerability mapping requires the integration of hydrogeological, topographic, and soil data within a GIS environment using

ArcGIS software (Merchant *et al.*, 1987). These datasets were used to generate the thematic layers required for the DRASTIC model.

Groundwater depth was determined from the difference between the Digital Elevation Model (DEM) and the piezometric surface established from 29 water points measured during the May 2019 field campaign. This approach enabled the identification of shallow groundwater areas considered more vulnerable to contamination.

The aquifer recharge was estimated based on the calculation of the regional water balance. The results revealed a pronounced water deficit, mainly attributed to low precipitation and high evaporation rates. Nevertheless, a significant anthropogenic recharge was identified, resulting primarily from the infiltration of agricultural drainage water and domestic wastewater. A detailed analysis of land use maps, combined with regional water management data—covering both water supply and sanitation systems, as well as agricultural water use related to irrigation—made it possible to quantify the aquifer recharge within the study area.

The aquifer material composition was determined through the analysis of twenty borehole logs provided by the National Agency for Water Resources (ANRH). Interpretation of these logs made it possible to differentiate between the saturated and unsaturated zones and to construct a representative lithological cross-section of the aquifer formation. These data are essential for assessing the filtration capacity of the medium and the potential migration rate of pollutants through geological layers.

The soil characteristics were extracted from the soil map of southern Algeria, which was georeferenced and clipped according to the study area boundaries. This step enabled the identification of the spatial distribution of different soil types—such as sands, silts, and clays—and the assessment of their respective permeability. The soil type plays a crucial role in the infiltration process and largely determines the vertical migration of contaminants toward the groundwater table.

The topography of the region was analyzed using the slope function of ArcMap applied to the Digital Elevation Model. This process produced a slope map highlighting the elevation variations within the study area. Areas with low slope gradients promote water infiltration and increase pollution vulnerability, whereas steep-slope areas favor runoff and reduce the risk of direct contamination (Wei *et al.*, 2022).

Finally, the hydraulic conductivity was determined from pumping tests performed on several wells tapping the shallow aquifer within the study area.

Validation of Groundwater Vulnerability Maps

The reliability of the groundwater vulnerability map was assessed by comparing it with the spatial distribution of the Groundwater Pollution Index (PIG). A strong spatial correlation between areas of high vulnerability and those exhibiting elevated PIG values suggests a general agreement between vulnerability patterns and groundwater quality indicators. This consistency indicates that the map accurately represents the zones most exposed to contamination. However, a comprehensive validation also requires field observations and chemical analyses to further enhance the accuracy and credibility of the results (Baalousha, 2006; Jamrah *et al.*, 2008; Secunda *et al.*, 1998).

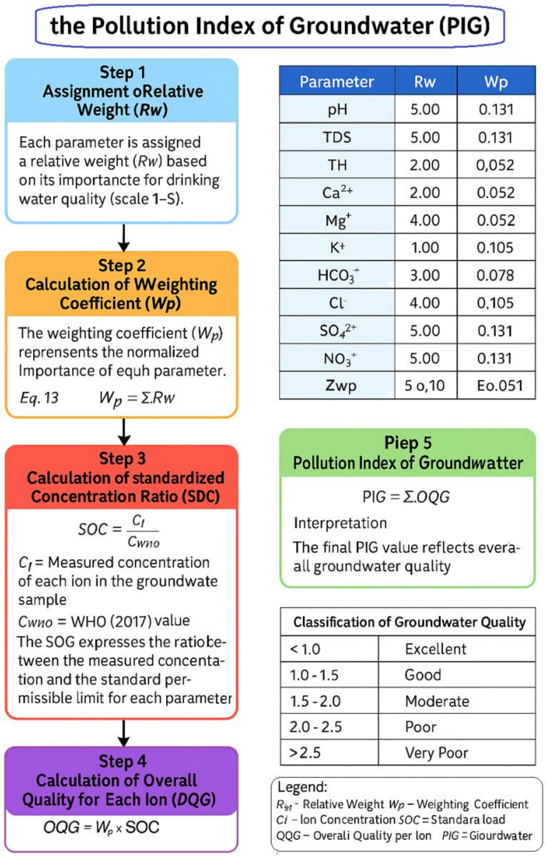

Figure 4. Flowchart summarizing the calculation procedure for the PIG

The PIG method is employed to assess groundwater contamination, primarily associated with anthropogenic factors, such as the infiltration of irrigation water—often enriched with chemical fertilizers—as well as domestic and sewage effluents infiltrating the soil in the absence of efficient wastewater treatment systems. The PIG approach, first introduced by Subba Rao (2012), is based on the integration of various physicochemical parameters. It consolidates all water quality variables into a single, unified indicator, as emphasized by several researchers (Lakhdari and Bouselsal, 2024; Subba Rao and Chaudhary, 2019).

Moreover, the PIG framework enables a comparative assessment of groundwater quality across different sampling sites and facilitates the monitoring of its temporal variations. The evaluation of water quality using the PIG technique follows five principal stages, as summarized in the flowchart presented in Figure 4 (Verma and Singh, 2021; Kharroubi *et al.*, 2024).

RESULTS AND DISCUSSION

Parameters of the DRASTIC Index

Depth to water level (D)

Groundwater depth in the shallow aquifer ranges from 0 to 15 m (Fig. 5a).

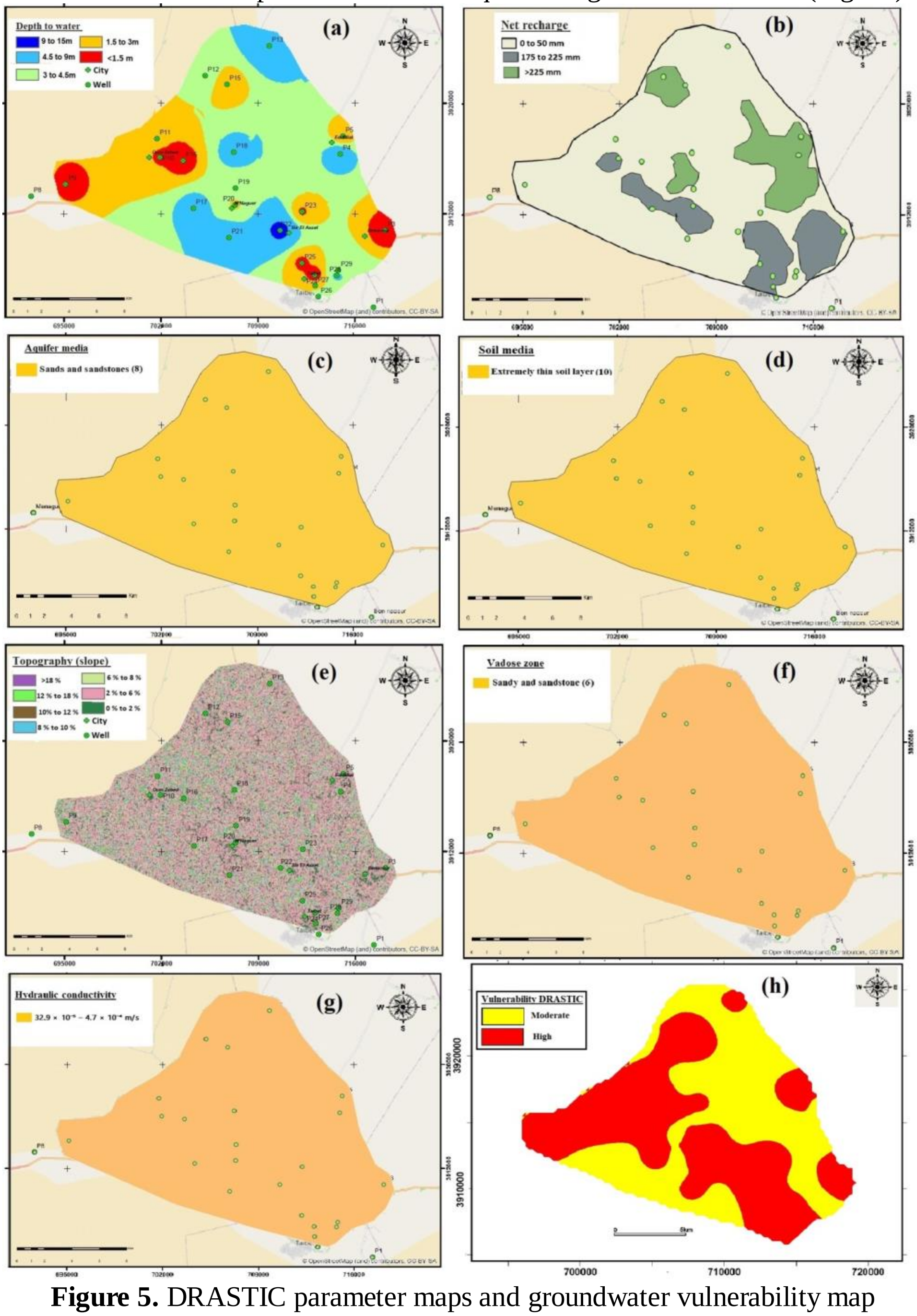

Figure 5. DRASTIC parameter maps and groundwater vulnerability map

Urban areas such as Taibet, Bennacer, El Mnagueur, and Oum Zbad show very shallow groundwater levels (0–3 m), mainly due to wastewater infiltration, corresponding to high DRASTIC ratings (9–10). Agricultural zones display intermediate depths (3–9 m) associated with irrigation return flows and were assigned moderate to high ratings (5–9), whereas desert areas exhibit deeper groundwater levels (9–15 m) corresponding to lower vulnerability ratings (3–5). According to the DRASTIC classification, shallow groundwater areas are considered more vulnerable to contamination (Aller *et al.,* 1987; Taheri et al., 2024).

Net recharge (R)

Recharge in the study area is mainly controlled by anthropogenic inputs, particularly irrigation return flows and wastewater infiltration, while natural recharge remains very limited because of low rainfall and high evaporation rates under arid climatic conditions. Based on satellite imagery and land-use analysis, three main recharge zones were identified: agricultural areas, urban areas, and desert zones (Maliva, 2020; Bouselsal *et al.,* 2015b).

Agricultural areas, representing about 8% of the study area, receive recharge mainly from irrigation return flows, with estimated recharge values exceeding 225 mm and a DRASTIC rating of 9 (Fig. 5b). Urban zones, covering approximately 7% of the area, are recharged by domestic wastewater infiltration due to the partial absence of sewage networks; recharge values range from 100 to 175 mm and correspond to a rating of 6. In contrast, desert areas occupy 85% of the region and exhibit very limited recharge (<50 mm) because of scarce precipitation and intense evaporation, resulting in a low DRASTIC rating of 1.

Aquifer media (A)

The aquifer media of the shallow aquifer were characterized using borehole log analysis and the hydrogeological cross-section established for the Taibet region (Fig. 5c). The aquifer thickness ranges between 25 and 60 m, and the saturated zone is mainly composed of sands and sandstones. Due to their high permeability and porous structure, these formations facilitate the rapid migration of contaminants toward groundwater. According to the DRASTIC classification, this lithological unit was assigned a rating of 8.

Soil media (S)

Soil characteristics strongly influence contaminant infiltration and groundwater vulnerability (Aller *et al.,* 1987; Patel *et al.,* 2022). In the study area, the soil cover is predominantly composed of aeolian dune sands characterized by very low organic matter content due to the arid climate and sparse vegetation. These sandy soils promote rapid infiltration and make agricultural activities highly dependent on fertilizers and soil amendments. Consequently, a DRASTIC rating of 10 was assigned to this soil unit, reflecting the absence of a well-developed protective soil layer (Fig. 5d).

Topography (T)

Topography influences the balance between infiltration and runoff, with low-slope areas generally favoring groundwater recharge (Maliva and Missimer, 2012). In the study area, elevations range from 77 to 130 m and slope values vary between 1% and 18% (Fig. 5e). This variability is related to the geomorphology of the Grand Erg Oriental, dominated by sand dunes and interdunal plains. Urban and agricultural activities are mainly concentrated in the relatively flat areas between dunes, where slopes generally range from 2% to 6%. These sectors promote infiltration and were assigned a high DRASTIC rating of 9.

Impact of vadose zone (I)

The vadose zone acts as a natural protective barrier limiting contaminant migration toward groundwater (Vrba and Zaporozec, 1994). Borehole log analysis (Fig. 1) shows that the unsaturated zone generally does not exceed 12 m in thickness and is mainly composed of Quaternary sands and sandstones (Fig. 5f and Fig. 6). These permeable formations, locally interbedded with sandy and gypsiferous clays, facilitate the downward transfer of contaminants toward the shallow aquifer. Accordingly, this lithological unit was assigned a DRASTIC rating of 6.

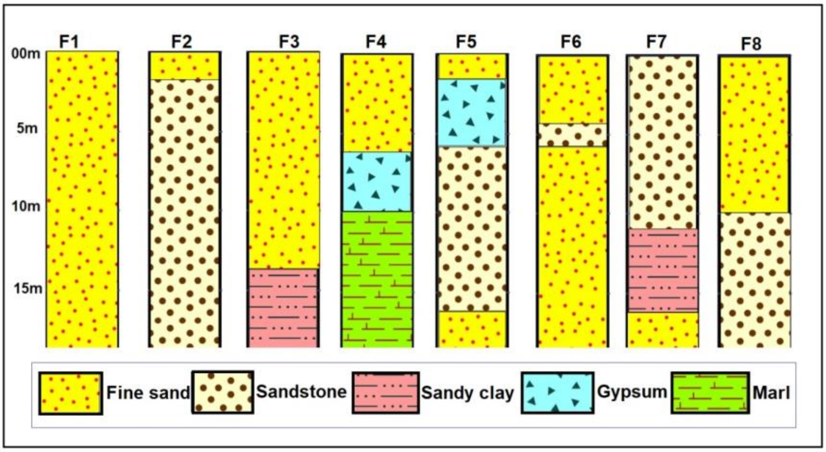

Figure 6. Representative lithological logs of boreholes intersecting the shallow aquifer

Hydraulic conductivity (C)

The hydraulic conductivity plays a crucial role in controlling the flow velocity of groundwater within the saturated zone, thereby influencing the migration of pollutants. According to the pumping test results conducted in the Taibet region, the average permeability coefficient of the shallow aquifer ranges from 32.9x10-5 to 4.7x10-4 m/s (Fig. 5g). Based on the DRASTIC method, a rating value of 6 was assigned to this class. This parameter indicates a moderate capacity of the aquifer to transmit pollutants through the subsurface environment, which is associated with a considerable risk of rapid contaminant dispersion.

DRASTIC vulnerability map

The overall vulnerability index was established after assessing the sensitivity of each DRASTIC parameter to contamination. The processed data were subsequently combined to generate the groundwater vulnerability map (Fig. 5h). In the investigated area, the vulnerability index ranges from 126 to 186, indicating overall moderate to high sensitivity levels. Accordingly, the map distinguishes two main vulnerability classes: moderate and high.

The moderate vulnerability class covers 47.28% of the total area, while the high vulnerability class occupies 52.72%. Spatial analysis clearly shows that areas with intense human activity exhibit the highest vulnerability levels. This is mainly due to the shallow depth of the water table and to significant recharge resulting from the infiltration of wastewater, domestic effluents, and agricultural drainage water. Conversely, sparsely populated sectors and desert areas display moderate vulnerability. This pattern is driven by deeper groundwater levels and nearly negligible recharge under the region's arid climatic conditions. However, it is important to note that moderately vulnerable areas may still be affected by the diffuse migration of contaminants originating in highly vulnerable zones, due to the regional flow of groundwater.

These results underscore the pressing necessity to establish effective groundwater protection actions and to implement sustainable management approaches designed to enhance water quality and maintain the aquifer's vital function for the local community.

The obtained vulnerability patterns highlight the strong influence of hydrogeological conditions and anthropogenic activities on groundwater quality degradation in the Taibet region. In this arid Saharan environment, the combination of shallow groundwater levels, permeable formations, irrigation return flows, and intensive agricultural practices may enhance the infiltration and accumulation of dissolved salts and contaminants within the aquifer system. Similar studies conducted in arid and semi-arid regions have shown that groundwater vulnerability is strongly controlled by the interaction between natural hydrogeological factors and land-use pressure.

The vulnerability mapping approach adopted in this study therefore provides useful preliminary support for identifying sensitive areas exposed to groundwater degradation risks and may assist local authorities in improving groundwater management strategies. In regions such as Taibet, where groundwater constitutes the principal water resource for agriculture and domestic supply, the integration of vulnerability assessment with hydrochemical monitoring may contribute to the development of more sustainable irrigation practices and groundwater protection measures adapted to arid environmental conditions.

Sensitivity Analysis of the DRASTIC Model

To address the limitation related to the qualitative weighting of DRASTIC parameters, a sensitivity analysis was performed to evaluate the relative contribution of each factor to the vulnerability index (Souleymane *et al.*, 2017; Yang *et al.*, 2017). The results indicate that depth to the water table (23.1%), recharge (19.8%), and the vadose zone (17.1%) are the most influential parameters (Fig. 7). Together, these three factors account for nearly 60% of the total influence, suggesting that groundwater vulnerability in the study area is primarily controlled by infiltration processes and vertical water transfer.

This dominance can be explained by the physical characteristics of the environment, which are typical of Saharan settings. The study area is characterized by relatively homogeneous geological formations, a generally flat topography, and a tabular structural organization. These features limit the variability of parameters related to the aquifer media, soil, and hydraulic conductivity, and significantly reduce the influence of topography (4.6%). Under such conditions, depth to groundwater and recharge become the most critical factors, as they directly control the intensity and rate of infiltration toward the aquifer.

The aquifer media (13.7%), soil (11.4%), and hydraulic conductivity (10.3%) show intermediate contributions, reflecting a secondary role in a relatively homogeneous geological context. This homogeneity limits their capacity to generate significant spatial contrasts in vulnerability.

These findings are consistent with the contamination mechanisms observed in the study area. The dominance of infiltration processes explains the high sensitivity of the aquifer to surface inputs, particularly the infiltration of wastewater in urban areas where the sanitation network is only partially developed, as well as the leaching of chemical fertilizers and irrigation return flows in agricultural zones. Under arid climatic conditions, characterized by intense evaporation, these processes are further amplified, promoting both the concentration of pollutants and their downward migration toward the groundwater.

Overall, the sensitivity analysis confirms that groundwater vulnerability in the study area is mainly governed by depth to the water table and recharge, in agreement with the prevailing hydrogeological conditions and local anthropogenic pressures.

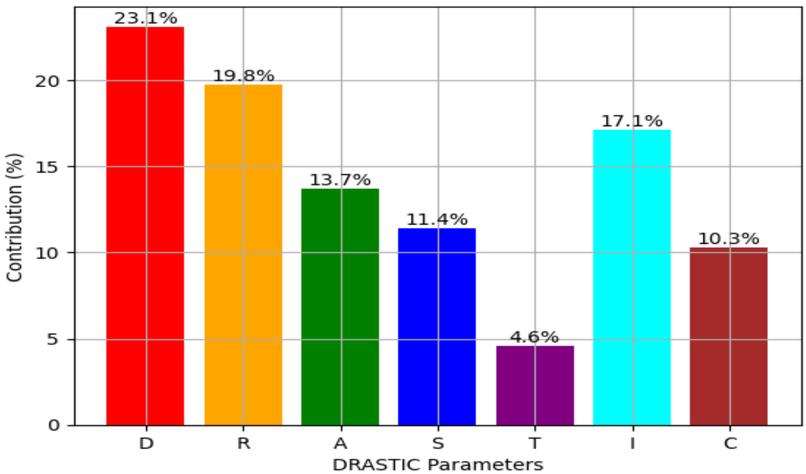

Figure 7. Sensitivity analysis of DRASTIC parameters

Hydrochemical characterization of groundwater

Physicochemical properties and hydrochemical facies

The analysis of the physicochemical parameters of groundwater samples from the shallow aquifer of the Taibet region reveals a significant variability in water composition (Fig. 8a). The pH values range from 7.3 to 8.2, indicating neutral to slightly alkaline conditions. Total dissolved solids (TDS) show a wide variation, ranging from 2500 to 4600 mg/L, reflecting a high degree of mineralization. Sulfate concentrations vary between 950 and 4400 mg/L, while chloride (Cl^-) contents range from 177 to 344 mg/L. Bicarbonate (HCO_3^-) concentrations also show considerable variability, ranging from 207 to 1317 mg/L. Among cations, calcium (Ca^{2+}) is the dominant ion, with concentrations between 400 and 979 mg/L, followed by sodium (Na^+) (34 to 1518 mg/L) and magnesium (Mg^{2+}) (46 to 391 mg/L). Potassium (K^+) concentrations remain relatively low, varying between 4 and 31 mg/L. Total hardness (TH), expressed as $CaCO_3$, ranges from 1456 to 4079 mg/L, indicating very hard water that is generally unsuitable for drinking without prior treatment (Hammad et al. 2023). Overall, the high concentrations of major ions indicate that groundwater in the shallow aquifer of Taibet is strongly mineralized. This mineralization is mainly controlled by water–rock interaction processes, particularly the dissolution of evaporitic formations, and may be further enhanced by anthropogenic inputs such as irrigation return flows and wastewater infiltration under arid conditions.

The Piper diagram (1944) was used to identify the hydrochemical facies of the Taibet shallow aquifer. As shown in Figure 8b, 90% of the samples belong to the Ca–Cl type, while one sample (W19) is classified as Ca–Mg–Cl and another (W12) as Na–Cl. The presence of these different water types reflects the complexity of mineralization processes and the influence of arid climatic conditions on groundwater resources. The Ca–Cl water type is generally considered an indicator of groundwater quality degradation in freshwater systems (Nouayti *et al.,* 2015; Dhaoui *et al.,* 2022; Wang *et al.,* 2024). In the northern Sahara, it is often interpreted as the result of mixing with more mineralized waters originating from deep confined aquifers, which are intensively exploited to meet the increasing demand for domestic and irrigation water (Bouselsal and Saibi, 2022). After use, these waters may infiltrate into the shallow aquifer as urban wastewater or irrigation return flows, thereby contributing to the progressive degradation of groundwater quality.

Assessment of Groundwater Contamination

The Groundwater Pollution Index (PIG), which integrates the influence of both geogenic processes and human-induced activities on groundwater quality (Lakhdari *et al.,* 2024; Bouselsal *et al.,* 2024), reveals markedly elevated pollution levels within the shallow aquifer of the Taibet region. It is observed that 95% of the samples exhibit a PIG value greater than 2.5, corresponding to a very high pollution level (Fig. 9).

This situation results from the combined influence of several factors. On the one hand, the geogenic origin of the contamination is linked to the excessive mineralization of groundwater caused by prolonged contact with formations rich in soluble salts such as gypsum and halite. These formations are highly susceptible to alteration and release ions into the water over time. On the other hand, anthropogenic factors significantly exacerbate the problem, as the aquifer is largely recharged by the infiltration of irrigation water—often enriched with chemical fertilizers—as well as domestic wastewater and sanitation effluents that percolate into the soil due to the absence of efficient sewerage systems.

Furthermore, the lack of dense vegetation cover, low rainfall, and the recurrence of drought periods contribute to increased ion concentrations, thereby further intensifying pollution levels.

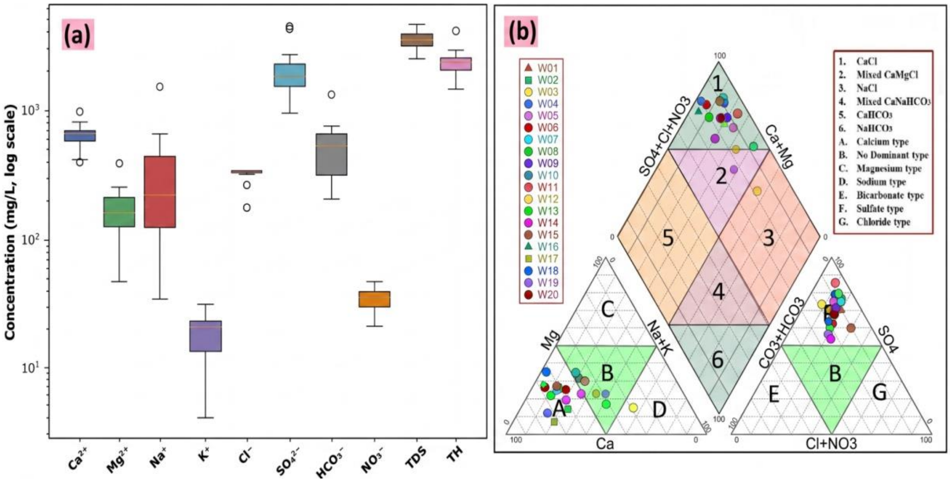

Figure 8. Boxplot showing the chemical composition (a) and water type (b) of groundwater of Taibet

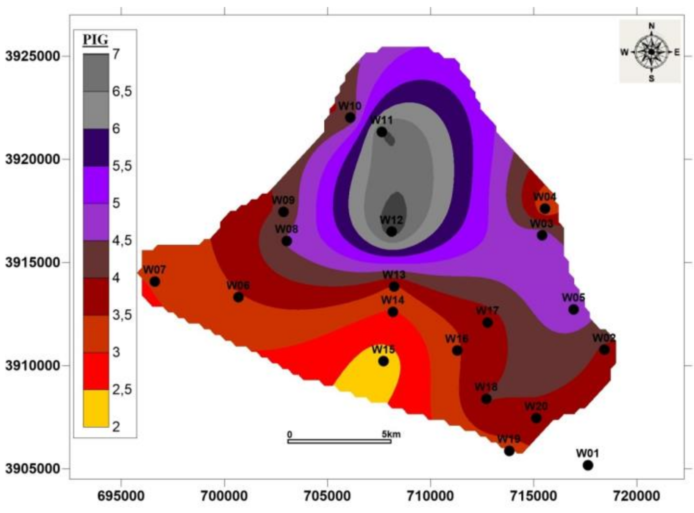

Figure 9. Spatial variation of the PIG in the study area

The nitrate distribution map (Fig. 10) makes it possible to assess the degree of groundwater contamination by nitrates, which are primarily of anthropogenic origin. Concentrations below 10 mg/L are generally considered natural or indicative of low-level contamination (Houari *et al.*, 2024). In contrast, higher values clearly signal pollution linked to human activities, particularly untreated or poorly treated wastewater, sanitation effluents, and agricultural drainage, as observed in the study area.

Spatial distribution analysis indicates considerable nitrate enrichment in the shallow aquifer, with concentrations varying between 21 and 47 mg/L. Such elevated values clearly demonstrate the strong impact of anthropogenic activities on groundwater quality. Except for two boreholes, all analyzed wells show elevated NO_3^- concentrations, varying from 30 to 47 mg/L. These results confirm substantial nitrate pollution affecting the shallow aquifer and highlight the vulnerability of the groundwater system to anthropogenic pressures.

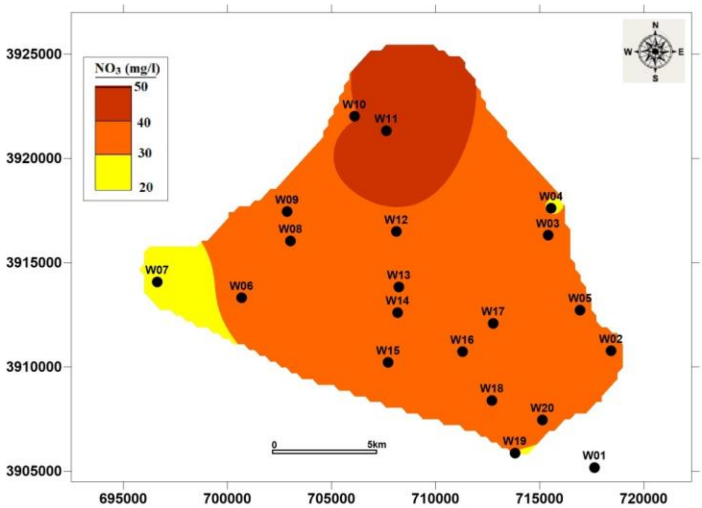

Figure 10. Spatial variation of nitrate concentrations in the study area

Validation of the DRASTIC Vulnerability Model

Relationship between DRASTIC index and groundwater quality

Spearman correlation curves (Fig. 11) highlight moderate positive relationships between the DRASTIC index and groundwater quality parameters, particularly nitrates (NO_3^-) (ρ≈0.53), total dissolved solids (TDS) (ρ≈0.57), and the groundwater pollution index (PIG) (ρ≈0.43). The observed correlations were statistically significant at $p<0.05$, although they should be interpreted cautiously due to the limited sample size. These results indicate an overall agreement between areas of high vulnerability and zones affected by groundwater quality degradation, suggesting that hydrogeological conditions favorable to infiltration play a key role in the transfer of pollutants to the aquifer.

This agreement can primarily be explained by the influence of anthropogenic pollution sources. In urban and peri-urban areas, the partial coverage of the sanitation network promotes the direct infiltration of untreated wastewater into the subsurface. These infiltrations constitute a major source of nitrates and dissolved salts, particularly in areas where domestic effluents are not adequately collected. The high vulnerability of these zones therefore facilitates the vertical transfer of contaminants into groundwater.

In addition, agricultural activities contribute significantly to this degradation. The intensive use of chemical fertilizers, combined with irrigation return flows, leads to substantial leaching of nitrates into the aquifer. This process is particularly pronounced in areas with frequent irrigation, which enhances the percolation of nutrient-rich waters. Consequently, the spatial overlap between vulnerable zones and intensively cultivated areas explains the positive relationship observed between the DRASTIC index and nitrate concentrations.

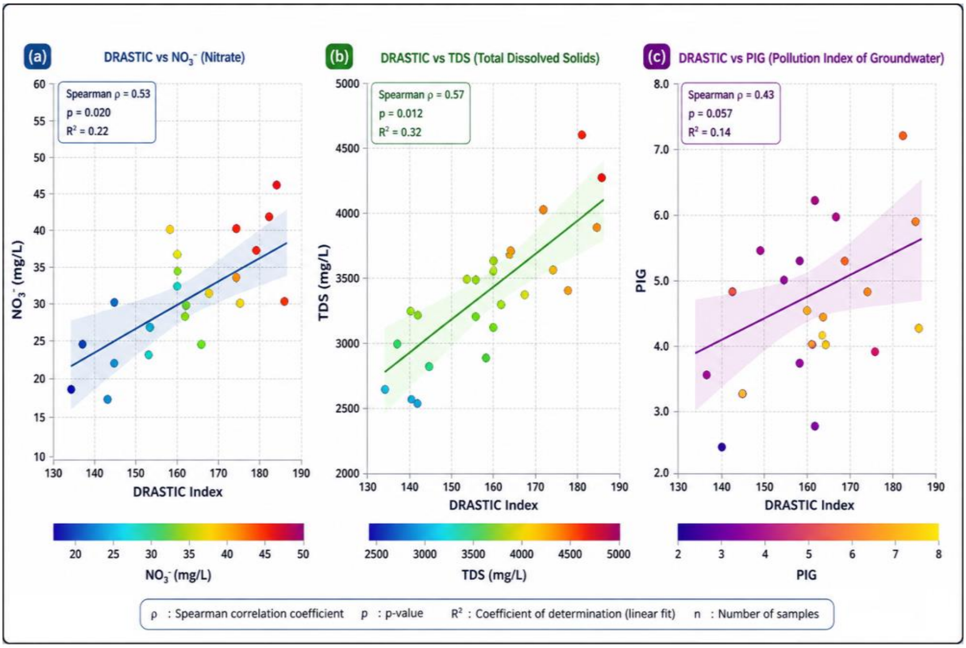

Figure 11. Spearman correlations between the DRASTIC index and groundwater quality parameters: (a) NO_3^-, (b) TDS, and (c) PIG. The points represent the wells (n=20), the colors indicate parameter intensity, and the lines correspond to linear fits. The results reveal moderate positive correlations, more pronounced for TDS

The stronger correlation observed with TDS reflects the combined effects of mineralization processes and arid climatic conditions (Bera *et al.*, 2021). Intense evaporation, characteristic of the region, leads to the concentration of dissolved salts in infiltrating waters, thereby increasing TDS values. This process acts in synergy with anthropogenic inputs, resulting in a progressive increase in salinity within vulnerable areas.

The weaker correlation with the PIG index can be attributed to its composite nature, as it integrates multiple hydrochemical parameters, which may introduce partial redundancy with the variables used in the analysis. Consequently, although this index provides a comprehensive overview of groundwater quality, it does not represent a fully independent indicator for model validation.

However, despite this overall consistency, the dispersion of data points indicates a moderate relationship between vulnerability and pollution, reflecting the influence of spatially heterogeneous anthropogenic factors. This variability is associated with the uneven distribution of urban areas characterized by partially developed sanitation systems, which favor wastewater infiltration, as well as with agricultural practices (chemical fertilizers and irrigation return flows) and the irregular distribution of seasonal crops. Arid climatic conditions, marked by intense evaporation, further enhance solute concentration. Therefore, although the DRASTIC model generally reflects intrinsic vulnerability, the observed moderate correlation suggests that groundwater pollution is strongly controlled by local anthropogenic factors, and the results should be interpreted as an overall consistency rather than a strict validation of the model.

Exploratory SOM Analysis of Groundwater Quality and Vulnerability

The Self-Organizing Map (SOM) approach was used as a complementary exploratory visualization tool to examine the relationships between groundwater quality indicators and the DRASTIC vulnerability index. This unsupervised method groups groundwater samples according to their hydrochemical similarity based on nitrate concentrations, the Pollution Index of Groundwater (PIG), and DRASTIC values. The SOM was trained using a 3×3 grid with normalized input data and a decreasing learning rate over 1000 iterations. By preserving the topological structure of multidimensional data, SOM offers a useful visualization of the overall behavior of the aquifer system and helps to identify patterns between vulnerability and contamination (Yang *et al.*, 2012).

In the present study, the SOM map (Fig. 12) shows that wells with relatively high nitrate and PIG values—particularly W11, W12, W02, W08, W09, W17, and W18—tend to cluster within nodes corresponding to areas characterized by higher DRASTIC values (170–186). This clustering indicates a general consistency between zones of higher intrinsic vulnerability and areas affected by groundwater contamination. Similarly, wells classified as moderately vulnerable are grouped into intermediate clusters reflecting moderate levels of pollution, further supporting the overall coherence of the results.

However, some wells (W05, W06, and W15) show discrepancies between DRASTIC values and measured pollution levels. These differences can be attributed to localized anthropogenic influences, such as wastewater infiltration or agricultural activities, as well as site-specific conditions that are not fully captured by the intrinsic parameters of the DRASTIC model.

Overall, the SOM results highlight a general agreement between groundwater vulnerability and contamination patterns. Nevertheless, due to the use of partially related variables, the SOM approach should be considered as an exploratory and complementary method rather than a strict validation tool.

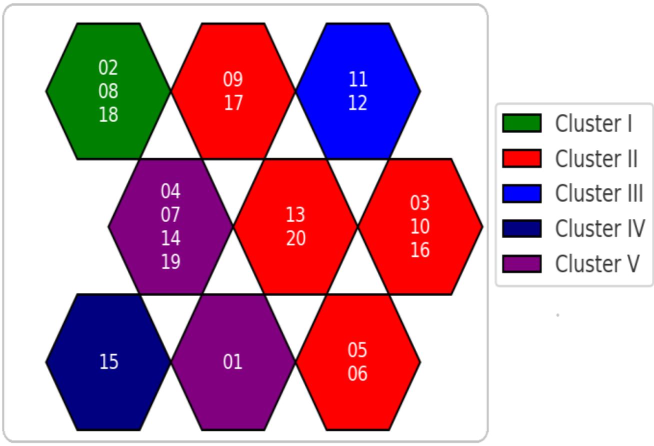

Figure 12. SOM-based clustering of wells using PIG, NO_3^- and DRASTIC

Study limitations and perspectives

This study presents certain limitations, particularly related to the relatively small number of samples (n=20), which significantly limits the statistical robustness of the analyses and reduces the spatial representativeness of the results. In addition, the lack of independent data on land use and precise pollution sources does not allow for a detailed quantification of the impact of anthropogenic activities on groundwater quality.

In this context, the future integration of a detailed land use map would enable a better characterization of the spatial distribution of pollution sources and improve the interpretation of the results. Furthermore, the use of isotopic tools, particularly oxygen ($\delta^{18}O$), hydrogen (δ^2H), and nitrate isotopes ($\delta^{15}N$, $\delta^{18}O$-NO_3), would provide a more accurate identification of water origin and contamination sources (e.g., wastewater, chemical fertilizers, irrigation return flows).

These approaches would contribute to a deeper understanding of the mechanisms controlling groundwater pollution and enhance the reliability of vulnerability assessment in the study area.

CONCLUSIONS

The integrated assessment conducted in the Taibet region demonstrates that the shallow aquifer is highly vulnerable to contamination and currently exhibits significant levels of pollution driven by both natural geochemical processes and intense anthropogenic pressures. The DRASTIC model identifies more than half of the study area as highly vulnerable, a result that aligns closely with the elevated concentrations of nitrates and the very high PIG values observed across the majority of sampled wells. The SOM analysis revealed an overall consistency between the DRASTIC vulnerability indices and the observed contamination indicators. Nevertheless, due to the exploratory nature of the method and the limited sample size, this agreement cannot be considered a strict statistical validation of the model. However, the absence of independent validation data and the relatively small sample size (n=20) limit the robustness of the findings, and thus the results should be interpreted with caution, particularly in terms of model validation and spatial generalization. In addition, the few discrepancies identified—mainly related to localized anthropogenic inputs such as irrigation return flows and wastewater infiltration—highlight the limitations of vulnerability models that do not fully account for spatial variability in human activities.

Overall, this work underscores the urgent need for targeted groundwater protection strategies, including improved wastewater management, optimized irrigation practices, and continuous monitoring of groundwater quality. Implementing these measures is essential to preserving the long-term sustainability of the shallow aquifer, which remains the primary source of water for domestic, agricultural, and economic activities in this arid region.

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