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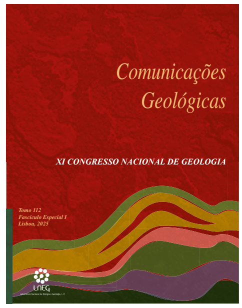
Groundwater vulnerability to nitrate contamination in an arid area

Vulnerabilidade da água subterrânea para nitratos numa região árida



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Abstract: One of the major challenges in assessing groundwater vulnerability is the factors number and weight assigned. Therefore, to improve groundwater vulnerability assessment, a model independent of weight assignment errors must be considered. Groundwater specific vulnerability index (SVI) was applied in the region of Gabès (Tunisia). Intrinsic vulnerability index (IVI) assessment was firstly determined by the arithmetic mean calculation of index overlay method (IOM), based on the Depth of aquifer (D), annual average Precipitation (P), Lithology of the vadose zone (L) and percent of Slope (DPLS). Then SVI was assessed by linking new factors (Land Use and NO_3^-) to IVI. A total of one hundred groundwater samples were analysed for NO_3^-, exceeding 50 mg L^{-1}. The spatial distribution of IVI shows four vulnerability classes: low (15%), moderate (35%), high (23%) and very high (27%). About 95% of the area registered high SVI values. This situation reinforces water-saving irrigation actions for adequate groundwater management.

Keywords: nitrate contamination, SVI, groundwater management, Gabès region, Tunisia.

Resumo: Um dos principais desafios na avaliação da vulnerabilidade da água subterrânea é o número e o peso dos fatores considerados, pelo que deve ser considerado um modelo independente de erros. A vulnerabilidade da água subterrânea na região de Gabès (Tunísia) foi determinada através do Índice de Vulnerabilidade Específico (SVI). Inicialmente é calculado o índice de vulnerabilidade intrínseca (IVI), considerando a profundidade do aquífero (D), precipitação média anual (P), litologia da zona vadosa (L) e percentagem de declive (DPLS). O índice SVI resulta da introdução de novos fatores – Uso do Solo e NO_3^-. Um total de cem amostras de água subterrânea foi colhido, registando um teor de NO_3^- superior a 50 mg.L^{-1}. A distribuição espacial do índice IVI mostra quatro classes de vulnerabilidade: baixa (15%), moderada (35%), alta (23%) e muito alta (27%). Cerca de 95% da área regista valores de SVI elevados. Os resultados obtidos reforçam a necessidade de adequadas práticas agrícolas na gestão da água subterrânea.

Palavras-chave: Contaminação em nitratos, SVI, gestão da água subterrânea, região de Gabès, Tunísia.

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1. Introduction

Groundwater, particularly in arid and semi-arid regions, present a critical resource for human survival, and worldwide is increasingly threatened by anthropogenic activities (Hamed *et al*., 2018). Groundwater pollution, exacerbated by human actions, is a global environmental pollution concern with widespread implications (*e.g.* Heib *et al*., 2020; He *et al*., 2019; Yopasá-Arenas and Fostier, 2018; Mouici and Rouabhia, 2017; Rouabhia *et al*., 2012). Tunisia, in particular, faces groundwater contamination challenges in various areas. In the southern Sahara aquifer system, petroleum and brine flows have contaminated groundwater, leading to elevated organic pollutant levels and salinity (Missaoui *et al*., 2023a,b; Abdelkarim *et al*., 2022a). Central and southern Tunisian region have rising nitrate pollution due to uncontrolled agricultural pesticide and fertilizer applications (Besser *et al*., 2018). Accurate tools on groundwater vulnerability assessment are crucial, attending to local geology, tectonic, and hydrodynamic characteristics (Abdelkarim *et al*., 2023a; Missaoui *et al*., 2022; Hadji *et al*., 2014). Groundwater nitrate contents could be associated to natural and/or human activities. Natural groundwater contains around 10 mg L^{-1} of nitrates (WHO, 2016) and the main source of high nitrate levels is associated to agricultural activities (*e.g.* fertilizers). Agricultural expansion and global food demands increase, requires groundwater protection to nitrate pollution. Groundwater vulnerability assessment tools are crucial on pollution prevention. Groundwater vulnerability models, like SYNTACS, PLEIK, and DRASTIC, have been applied, relying on factors including vadose and saturated zone properties, recharge rates, and soil type (Missaoui *et al*., 2022; Ncibi *et al*., 2020; Antunes *et al*., 2018). Accurate recharge estimation is essential for assessing pollutant transport from the vadose to the saturated zone, but it remains challenging due to reliance on climatic data collection and variable accuracy. The vadose zone's lithology and soil type have a crucial role in pollutant attenuation, with clay-rich soils reducing intrinsic permeability and slowing pollutant migration (Abdelkarim *et al*., 2023b; Hamed *et al*., 2018). Aquifer vulnerability decreases with groundwater depth increase, although aquifer properties, as media type and hydraulic conductivity, influence pollutant transport and migration (Abdelkarim *et al*., 2023a,b,c,d; Missaoui *et al*., 2022; Ncibi *et al*., 2020). Some models have incorporated quantitative aquifer factors and soil occupation. However, an appropriate weight to factors assignment also persists due to the complexity of the models. Complex models involving numerous factors and data sources have also been proposed with adequate geostatistical methodologies. In that context, the main purpose of this research is the groundwater vulnerability assessment to nitrate pollution, in Gabès region (Tunisia), considering the SVI index combined with groundwater NO_{3-} contents and Land Use (LU).

2. Geological setting

The study area is in the Gabès region, southeast of Tunisia, bounded by the Gulf of Gabès (East), Medenine region (South), and Kebili region (West; Figura 1). A Mediterranean climate with an arid bioclimatic stage and an average annual precipitation of about 200 mm/year dominates. The climate is influenced by two zones: the Sahara (South) and the Mediterranean Sea (East). Annual evaporation ranges from 1500 to 2000 mm year^{-1}, with temperatures between 4°C, in winter, and 45°C, in summer. Winds registered an average velocity of over 6 m s^{-1}, predominantly from southwest-northeast and south-north direction (Abdelkarim *et al*., 2022a). Surface water is scarce, and groundwater is the main water source for agricultural activities.

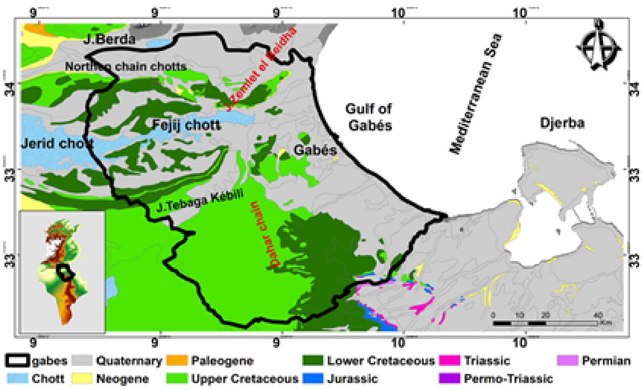

Figure 1. Geographical and geological setting of the study area.

Figura 1. Enquadramento geográfico e geológico da área de estudo.

The topography is characterized by a flat and monotonous landscape, with plains and plateaus rising 650 meters, in contrast with mountain areas (northern and central Tunisia). Some areas have steep margins, hills, and rare mountain ranges, like the Chotts Ranges (Agoubi et al., 2018). The region contains about 300 multidirectional faults and linear structures, with a dominant NNW–SSE direction, related to Miocene compressive tectonic activity (Msaddek et al., 2016; Zargouni, 1985; Dlala, 1995). The geology comprises Neogene and Cretaceous deposits. Cretaceous successions include Albian and Turoniann units, the former corresponding to dolomite, limestone, and marl, while the later contains dolomite, particularly on southeast region. Barremian units with clay and gypsum materials also occur (Abaab et al., 2021). Neogene units are composed of gypsum, clays, and sands, overlaid by Quaternary formations, primarily composed of clays and gypsum (Abdelkarim et al., 2023c; Agoubi et al., 2018).

3. Material and methods

A total of one hundred groundwater samples, from boreholes and wells, were collected in the study area, in March 2021 (dry season). The sampling network was designed to ensure the representation of the study area and developed within a research collaboration with the Regional Centre for Agricultural Research in Gabès (Tunisia). Nitrate groundwater content was determined "*in situ*" using a multi-parameter analyzer - C933 Multi-Parameter device with two-point calibration. The data collection process involved a multifaceted approach (Figura 2). Firstly, aquifer groundwater depth was determined at fifty-one wells and boreholes. Additionally, records of average annual precipitation, registered from 1980 to 2019, at eight rainfall stations were considered (DGRE, 2019). Furthermore, the lithology of the vadose zone was obtained from eighty boreholes and wells section profiles, and slope degree from the digital elevation model (DEM). Spatial Analyst Tools – Interpolation – was applied to produce raster maps of groundwater aquifer depth (D), precipitation (P), lithology (L), slope (S), nitrate groundwater concentration (NO_{3-}), and land use (LU).

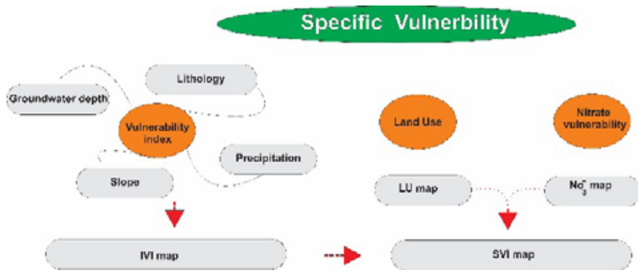

Figure 2. Methodology flowchart.

Figura 2. Fluxograma da metodologia.

Groundwater vulnerability assessment includes a systematic rating established for each factor, ranging from 1 to 10, and using the "Reclassify tool" integrated into the ArcGIS 10.5® software. These ratings were represented on a spatial vulnerability distribution to each factor and relative contribution to the final risk map. Nitrate groundwater content and land use were segmented into classes assigned with a rating between 1 and 10 (Table 1).

Table 1. Ratings for vulnerability factors

Tabela 1. Classificação para os fatores de vulnerabilidade

D (m)	P (mm)	L	S (%)	NO_{3-} (mg L-1)	Rating
> 50	< 110	Silt	> 18	< 10	1
45–50	110–120	Clay	15–18	10–15	2
40–45	120–130	Gypsum	12–15	15–20	3
35–40	130–140	Dolomite	9–12	20–25	4
30–35	140–150	Limestone	6–9	25–30	5
25–30	150–160	Sandy clay	5–6	30–35	6
20–25	160–170	Marl	4–5	35–40	7
15–20	170–180	Clayey sand	3–4	40–45	8
10–15	180–190	Sand	2–3	45–50	9
< 10	> 190	Sand and gravel	< 2	> 50	10

(D: groundwater aquifer depth; P: Annual average precipitation; L: Lithology of the vadose zone; S: slope)

Land Use classification considered three categories, including uncultivated and urban areas (rating 8), perennial crops (rating 9), and irrigated areas (rating 10). Specific Vulnerability Index (SVI) is computed through the overlay of NO_3^- groundwater content and LU with the Intrinsic Vulnerability Index (IVI), using the formula:

$$SVI = \frac{1}{k}\left(IVI + \sum_{j=1}^{k} Y_j/k\right)$$

Where Y_j - rating for j^{th} factors (NO_3^- and LU); k - factor number

To bolster the credibility of the SVI outcomes, a rigorous validation process was considered. The validation process drew nitrate groundwater data, with 75% of the data employed at the initial SVI computation, while the remaining 25% was preserved for validation purposes, ensuring the robustness of the vulnerability assessment methodology (Ncibi *et al*., 2020).

4. Results and discussion

The SVI index spatial distribution in the study area shows four vulnerability classes: low (15%), moderate (20%), high (35%), and very high (30%; Figura 3). Unlike previous studies, in which nitrate content was deployed for validation purposes, in this research NO_3^- groundwater content is an input factor of the model simulation, increasing the reliability and accuracy. The higher vulnerability area is concentrated in the coastal region, especially in the agricultural zones (Figura 3). This heightened vulnerability is primarily attributed to groundwater resources overexploitation and excessive chemical substances application associated to agricultural activities. Pesticide and fertilizers are essential components of agricultural practices; however, an excessive application could be toxic and pose a contaminant effect to environment and human health.

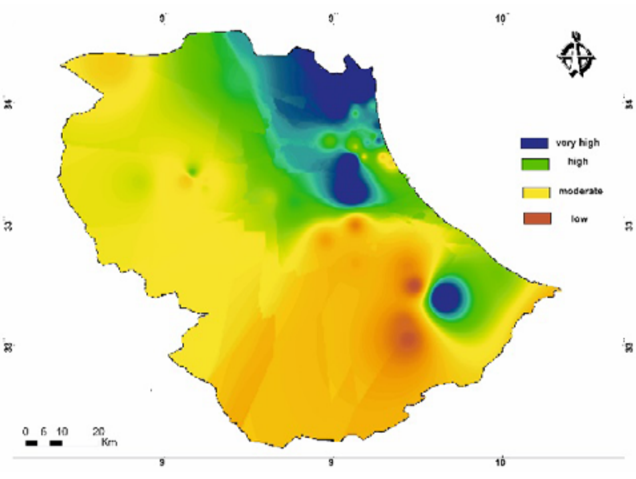

Figure 3. SVI spatial distribution on the study area.

Figura 3. Distribuição espacial do SVI na área de estudo.

The long-term exposure to pesticides is associated with several adverse health effects, including but not limited to respiratory and neurological disorders, carcinogenicity, reproductive impairments, and genotoxicity (Agoubi *et al*., 2018; Ben Alya *et al*., 2013). Some potentially toxic elements, such as cadmium, mercury, lead, arsenic, nickel, and zinc, are associated to agricultural contamination and soil salinization processes. These multifaceted environmental issues show the necessity of urgent adoption of sustainable and ecologically agricultural practices. It is imperative to reduce groundwater resources exploitation and to define adequate agricultural practices to harmonize productivity and environmental preservation. In this pursuit, the judicious use of chemical inputs, diligent monitoring of pesticide and fertilizer application, and the implementation of soil remediation measures to mitigate potentially toxic elements contamination are crucial.

The vulnerability attributes detailed in this study have a significant contribution on nitrate groundwater contamination dynamics in the region of Gabès (Tunisia). Several factors, including fault systems, permeable formations, and tectonic events, are crucial to groundwater's vulnerability to nitrate contamination and to the hydrogeological behavior of aquifer systems (Besser *et al*., 2018; Ben Alaya *et al*., 2014). Coastal recharge, influenced by the proximity of the piezometric level to the surface, contributes to nitrate vulnerability (Figura 4), particularly due to intensive agricultural activities in the northeastern part of the region (Abdelkarim *et al*., 2022a,b). However, groundwater nitrate vulnerability is often limited to non-permanent flows, highlighting challenges in the sustainability of water resources (Abdelkarim *et al*., 2022a,b).

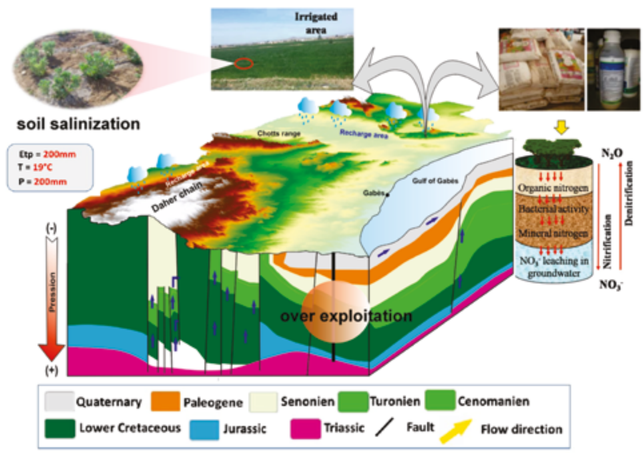

Figure 4. Conceptual model for groundwater nitrate vulnerability.

Figura 4. Modelo concetual da vulnerabilidade da água subterrânea para nitratos.

Moreover, Gabès region's structural configuration, coupled with tectonic events, significantly influences the hydrodynamic behavior of aquifer systems and, consequently, nitrate pollution (Abdelkarim *et al*., 2022a,b; Besser *et al*., 2018; Javadi *et al*., 2011). The occurrence of a permeable fault structure traversing the Continental Interlayer aquifer is another critical factor impacting nitrate vulnerability (Ben Alaya *et al*., 2014). This fault structure acts as a preferential pathway for vertical up-recharging, facilitating groundwater movement between different aquifer layers and increasing nitrate contamination risks. The vertical preferential pathways hold significant implications for nitrate vulnerability assessment and groundwater management. These structural attributes are supported by other investigations on the area (Besser *et al*., 2018; Ben Alaya *et al*., 2014), and consequent influence on nitrate groundwater vulnerability. Understanding these processes is imperative for effective groundwater resources management, particularly on groundwater overexploitation, scarce water recharge, human demands increase and nitrate contamination prevention. Therefore, it is crucial to develop sustainable water management practices to safeguard a future water resources availability in this region. Recent studies have explored innovative agricultural systems and technologies to enhance productivity while minimizing negative environmental impacts, particularly those related to nitrate groundwater vulnerability (Missaoui *et al*., 2023a,b; Besser *et al*., 2018).

Sustainable practices like precision agriculture, vertical farming, hydroponics, efficient irrigation methods (*e.g.* drip irrigation and micro-sprinklers), rainwater harvesting, and wastewater reuse have been described to reduce water discharge and nitrate contamination risks (Agoubi *et al*., 2018; Besser *et al*., 2018). The utilization of nano-fertilizers has gained attention for improving nutrient uptake efficiency and reducing nitrate losses, contributing to reduced nitrate vulnerability. However, further research is essential to assess the long-term environmental impacts and ensure safe implementation. Efforts to mitigate potential nitrate pollution risks through adequate management practices and environmentally friendly inputs have been considered. Continuous research is crucial to evaluate the sustainability and effectiveness of these approaches, particularly in addressing nitrate groundwater vulnerability associated to agricultural practices and consequently nitrate contamination risk.

5. Conclusions

In the Gabès region, the Neogenic aquifer system revealed an extensive groundwater vulnerability, considering Specific Vulnerability Index (SVI). This heightened risk is mainly concentrated in the northeastern region and results from a complex interplay of several factors. Land Use practices, especially agricultural activities, play a crucial role on vulnerability spatial distribution, with intensive farming activities acting as a significant source of groundwater potential contamination. Furthermore, the vadose zone, characterized by the coexistence of sandy and clayey sand deposits, intensify the aquifer's susceptibility to pollutants. The SVI method emerges as a powerful tool in groundwater vulnerability assessment. However, the full potential of SVI requires proactive and comprehensive policymaking processes on water resources management. Precision agriculture practices must be encouraged, promoting responsible application of inputs, and minimizing environmental contamination processes. Land use policies should be tailored to protect vulnerable areas, while educational initiatives should ensure that stakeholders have responsibility on groundwater management practices. Rigorous monitoring and regulation are essential to prevent groundwater over-extraction and potential contamination, complemented by innovative and sustainable agricultural practices. The present research is a relevant contribution to groundwater vulnerability in Gabès region and other semi-arid areas, and for future water resources availability.

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