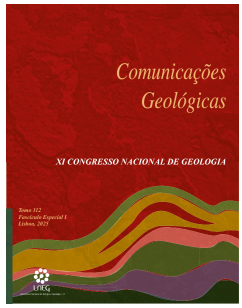
Comunicações Geológicas

Comunicações Geológicas (2025) 112, Especial I, 179-182
ISSN: 0873-948X; **e-ISSN**: 1647-581X

Assessment of groundwater vulnerability of fractured aquifers from arid regions

Avaliação da vulnerabilidade da águas subterrânea em aquíferos fraturados de regiões áridas



B. Abdelkarim[1, 2], I. M. H. R. Antunes[2*], N. Abaab[3], A. Tounekti[4], B. Agoubi[1]

DOI: https://doi.org/10.34637/8khq-q414

Recebido em 27/09/2023 / Aceite em 31/03/2024

Publicado online em abril de 2025

Artigo original
Original article

Abstract: Groundwater is the main water source of semi-arid regions. In these areas, it's crucial to establish appropriate strategies for evaluating the vulnerability of aquifer systems and their potential exposure to contamination, especially in fractured aquifers, which possess a naturally high vulnerability. The aquifer system from Gabès region, southeastern Tunisia, is a fractured medium exposed to intensive agricultural activities with excessive fertilizer use. This study introduces a novel vulnerability index by incorporating the contribution of medium into the DRASTIC vulnerability method. The obtained results reveal the presence of zones with different degrees of vulnerability: very low (9.6%), low (15%), moderate (22.9%), high (21.5%), and very high vulnerability (31%). The spatial distribution of this new vulnerability index proves to be a valuable tool for effective groundwater management and the identification of suitable locations for new wells and boreholes in the region of Gabès.

Keywords: vulnerability, DRASTIC modified, groundwater management, Artifitial Intelligence, Tunisia.

Resumo: Os aquíferos constituem a principal fonte de água nas regiões semiáridas. Nestas regiões é fundamental a definição de estratégias adequadas na avaliação da vulnerabilidade dos sistemas aquíferos e possível exposição a contaminação, em particular para aquíferos fraturados, face à sua elevada vulnerabilidade natural. O sistema aquífero da região de Gabes, sudeste da Tunísia, é um meio fraturado exposto a atividades agrícolas intensivas com uso excessivo de fertilizantes. Com este trabalho é apresentado um novo índice de vulnerabilidade, resultante da introdução da variável relativa à fracturação do meio no índice de vulnerabilidade DRASTIC. Os resultados obtidos mostram a ocorrência de zonas de vulnerabilidade: muito baixa (9.6%), baixa (15%), moderada (22.9%), elevada (21.5%) a muito elevada (31%). A distribuição espacial deste novo índice de vulnerabilidade é uma importante ferramenta para a gestão adequada da água subterrânea e na localização de novos de poços e furos na região de Gabès.

Palavras-chave: vulnerabilidade, DRASTIC modificado, gestão de água subterrânea, Inteligência Artificial, Tunísia.

[1] Institut Supérieur des Sciences et Techniques des Eaux de Gabès, Université de Gabès; LR: Applied Hydro-Sciences Laboratory Research Campus Universitaire, 6072 Zrig, Gabes, Tunisia

[2] Institute of Earth Sciences, Pole of University of Minho, Department of Earth Sciences, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

[3] Le Mans Université, Géosciences Le Mans, LPG UMR 6112, 72085 Le Mans, France

[4] University of Tunis El Manar, Faculty of Sciences of Tunis, 2092, Tunis, Tunisia

[*] Corresponding author / Autor correspondente: imantunes@dct.uminho.pt

1. Introduction

In recent years, Artificial Intelligence (AI) has revolutionized groundwater vulnerability assessment by addressing data limitations and enhancing the ability to understand and prevent contamination risks (Agoubi *et al.*, 2019; Antunes *et al.*, 2018: Abdelkarim *et al.*, 2023 a,b,d,c). Traditionally, various vulnerability methods like DRASTIC (Aller *et al.*, 1987), GOD (Foster, 1987) and AVI (Stempvoort *et al*., 1993) have been used to assess aquifer systems vulnerability. However, these methods often neglect the influence of rock fractures on groundwater pollution, despite the potential for serious contamination due to their high recharge and infiltration rates. To bridge this gap, a new parameter - fracture media (Fr) - will be proposed into the conventional DRASTIC model. A new vulnerability model - DRASTIC-Fr - proves to be effective in delineating vulnerable areas within fractured aquifer systems. This extended model includes fractured media (Fr) as the eighth parameter, complementing the traditional seven-parameter of DRASTIC vulnerability index (Aller *et al.*, 1987).

One of the primary challenges in aquifer vulnerability assessment is managing the uncertainties arising from expert judgments on the determination of weights and rates for the DRASTIC atributes (*e.g.* Aller *et al.*, 1987; Msaddak *et al.*, 2016; Missaoui *et al.*, 2023b). Some information related to local hydrogeological conditions, weights reflecting the significance of thematic layer datasets in vulnerability assessment, and interconnections indicating aquifer sensitivity to human-induced contaminants must be highlighted. To systematically address these uncertainties, the DRASTIC-Fr vulnerability index appraisal metrics as a structured framework for selecting thematic layer datasets and investigating potential sources of uncertainty.

To enhance the accuracy of the conventional DRASTIC method, which relies on prescriptive rates and weights and lacks direct measurements of intrinsic vulnerability, AI frameworks and machine learning processes, encompassing both unsupervised and supervised approaches, is a relevant contribution. A range of AI techniques, including Logistic Regression (LR), Genetic Algorithm (GA), Fuzzy Logic (FL), Artificial Neural Network (ANN), and Support Vector Machine (SVM) have been applied to automate parameter learning and classification from datasets without external intervention (Agoubi 2018; Missaoui *et al.*, 2022).

The presented study explores the integration of Multi Frameworks Technique (MFT) and Multi Models Approach (MMA) to map the spatial Aquifer Vulnerability Index (AVI) distribution, combining unsupervised and supervised machine learning techniques. The research incorporates two Multi-Frameworks Techniques (MFT) - Standard DRASTIC-Fr framework (SDF) and Fuzzy Membership

Framework (FMF), along with two Multi-Models Approaches (MMA) - Genetic Algorithm (GA) and Genetic Expression Programming (GEP) applied on the fracturated aquifer system from Gabès region (SE Tunisia).

2. Geological setting

The study area, in the southeastern of Tunisia, is defined by its proximity to the Gulf of Gabès in the east, the Medenine region in the south, and the Kebili region in the west (Figura 1).

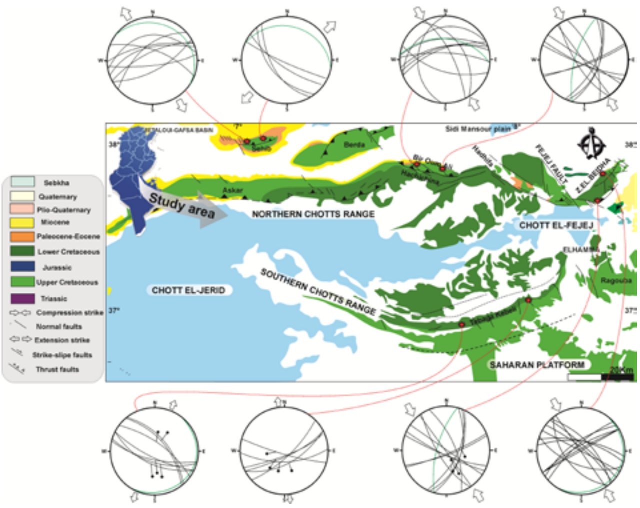


Figure 1. Geography and geology from the study area

Figura 1. Geografia e geologia da área de estudo

The area presents a Mediterranean climate characterized by arid bioclimatic conditions, with an average annual precipitation of 200 mm/year (Agoubi 2018; Abdelkarim *et al.*, 2023d). This climatic profile is influenced by two distinct factors: the arid Sahara Desert (south), and the temperate Mediterranean Sea (east). Annual evaporation rates range from 1500 to 2000 mm/year, and temperature has significant fluctuations, from 4°C to 45°C (Agoubi 2018; Abdelkarim *et al.*, 2023d). Prevailing winds, blowing predominantly from southwest-northeast and south-north directions, with an average velocity of 6 m/s, influence the region's climate (Abdelkarim *et al.*, 2022). Surface water resources are notably scarce and groundwater is the primary source for a wide spectrum of sectoral needs.

The area is relatively flat in a regular landscape, featuring plains and plateaus with elevations not exceeding 650 meters altitude. However, local regions feature steeper margins, hills, and occasional mountain ranges, such as the Chotts Ranges (Agoubi 2018). On the region there are approximately 300 multidirectional direction. This structural pattern suggests significant tectonic faults and linear geological structures, with a dominant NNW–SSE activity during the Miocene period (Zargouni, 1985; Dlala, 1995; Msaddek *et al.*, 2016). The study area encompasses a variety of lithologies, including Mio-Plioquaternary and Cretaceous sedimentary formations. The Cretaceous formations consist of Turonian and Albian rocks, with Barremian formations characterized by the presence of clay and gypsum materials (Abdelkarim *et al.*, 2023c). Albian formations comprise dolomite, limestone, and marl, while Turonian dolomite formations predominate in the southeastern part of the region. Mio-Pliocene formations consist of gypsum, clays, and sands, overlain by Quaternary formations primarily composed by clays, often with a gypsum crust (Abdelkarim *et al.*, 2023a; Agoubi 2018).

Considering the geological and dominant climatic factors in this region, groundwater management and vulnerability assessment are crucial. Groundwater vulnerability studies suggest relevant tools on water quality and availability (Bhering *et al.*, 2023). These studies are indispensable for devising informed strategies to address the challenges posed by agriculture, industry, and population growth, which have strained the groundwater resources from the Meknassy basin. The intensification of agricultural activities with excessive application of fertilizers and pesticides have been promoting groundwater contamination. Consequently, groundwater vulnerability assessment is essential for an effective management, including mitigation of contamination and ensuring sustainable water availability on the region.

3. Material and methods

The methodology integrates the DRASTIC.Fr method with Artificial Intelligence (AI) techniques for aquifer vulnerability assessment. Initially, the DRASTIC.Fr framework is employed, comprising parameters such as depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity, each assigned a rating based on their influence on groundwater vulnerability. Subsequently, AI methods are integrated to enhance the analysis. AI algorithms are utilized for data preprocessing, handling large datasets, and identifying patterns within various parameters, improving the accuracy of vulnerability assessments. Machine learning models, such as neural networks or decision trees, are trained using historical data to predict aquifer vulnerability based on the DRASTIC parameters and additional data sources like satellite imagery or geological surveys. Moreover, AI-based optimization techniques can refine model parameters to better fit observed vulnerabilities, increasing the robustness of predictions. Additionally, AI-driven spatial analysis techniques aid in mapping vulnerability zones and identifying areas requiring prioritized management interventions. Continuous learning and refinement of the AI models through feedback loops ensure adaptability to changing environmental conditions. This integrated approach leverages the strengths of both DRASTIC.Fr and AI methodologies, providing a comprehensive and accurate assessment of aquifer vulnerability for effective groundwater resource management.

The conventional DRASTIC model considers seven parameters, including deep of water (D), net recharge (R), aquifer media (A), soil type (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C; Aller *et al.*, 1987), assigned by a weight (w:1-5) and a rate (r: 1-10), reflecting the influence in the aquifer vulnerability. Aquifer Vulnerability Index (AVI) is expressed by the equation: AVI = $\Sigma(W_i{*}R_i)$, W_i= weight and R_i= rate assigned to each parameter. This index serves as a valuable tool for decision-makers, hydrogeologists, and environmental experts to identify areas with varying degrees of groundwater vulnerability to contamination sources.

In this survey, an intrinsic attribute – Frature media (Fr) was added

Table 1. Índice de vulnerabilidade DRASTIC-Fr modificado

Tabela 1. Modified DRASTIC-Fr vulnerability index

Parameter	Weight
D - Water depth	5
R - Net recharge	4
A - Aquifer media	3
S - Soil type	1
T – Topography	5
I - Impact of vadose zone	3
C - Hydraulic conductivity	3
Fr - Fracture media	3

to the Aquifer Vulnerability Index algorithm to define the modified DRASTIC-Fr (Table 1).

4. Results

The DRASTIC vulnerability index is a crucial tool for assessing groundwater vulnerability across diverse regions, offering insights into contamination risks and groundwater availability challenges (Aller *et al.*, 1987). Utilizing the DRASTIC-Fr approach in our study area provides valuable perspectives on potential contamination risks and groundwater availability challenges. The resulting DRASTIC-Fr index reveals five vulnerability classes: very low (9.6%), low (15%), moderate (22.9%), high (21.5%), and very high vulnerability (31%) (Figura 2)

Notably, areas in the southern part of the study region, characterized by factors such as recharge areas and limited pesticide use, exhibit lower vulnerability, aligning with the lower DRASTIC-Fr index values. Conversely, regions in the north, particularly near the chott region, face

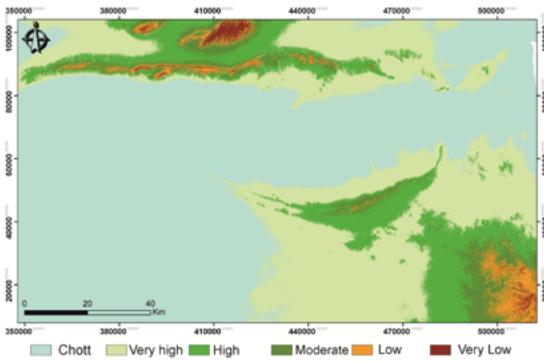


Figure 2. Vulnerability map of the study area.

Figura 2. Mapa de vulnerabilidade da área de estudo.

challenges related to lower water quality attributed to saltwater intrusion and intensive pesticide use in agriculture (Abdelkarim *et al.*, 2022). However, water quality tends to improve with the flow direction of aquifer systems. Additionally, high groundwater sodium concentrations in the southern part may stem from sedimentary Senonian lagoon formations, affecting both northern and southern coastal areas and posing challenges for irrigation practices. Areas like Elhamma stand out for their high permeability index values, indicating heightened vulnerability due to increased permeability. Overall, the groundwater vulnerability assessment in the Gabès region using the DRASTIC-Fr approach underscores the necessity for sustainable groundwater management practices. The spatial distribution of the index highlights areas of concern, emphasizing the urgent need for appropriate measures to safeguard and conserve groundwater resources (Abaab *et al.*, 2021; Abdelkarim *et al.*, 2023d).

5. Discussion

A modified technique for mapping the Aquifer Vulnerability Index (AVI) is proposed for fractured system aquifers. This approach - DRASTIC-Fr - introduces a new additional thematic layer relative to the presence of rock fractures (*i.e.* joints, fractures and faults). These structural elements are assessed based on the hydraulic impact on the aquifer system and their potential to facilitate the movement of pollutants into the subsurface. The parameter representing fractured media (Fr) plays a significant role in quantifying the vulnerability of areas near geological extensions and tectonized formations, shedding light on the potential impact of rock fractures to groundwater quality

In situations with limited datasets, especially in complex regions, the reliability of findings can be compromised. However, this study demonstrates that the results are substantiated through unsupervised and supervised learning methods. Additionally, the study explores the convergence and divergence of outcomes across two stages of multi-frameworks and multi-models.

Previous research has proposed various frameworks and models within AI domains to address spatial groundwater vulnerability challenges. Many of these approaches are rooted in the DRASTIC methodology, relying on the interpretation of coupled datasets from field and monitoring device inputs. Among these, the Basic DRASTIC framework (BDF) and Modified DRASTIC as Multi Frameworks Technique (MFT) are widely employed. For instance, Jang *et al.* (2017), Abdelakirm *et al.* (2022) and Missaoui *et al.* (2022; 2023a) demonstrated the use of high-resolution data and a genetic algorithm-based calibration method to assess aquifer system vulnerability. Similarly, Nadiri *et al.* (2018b) improved the Basic DRASTIC Framework's performance and introduced variations, such as Fuzzy-Catastrophe Framework (FCF). Additionally, other studies incorporated anthropogenic impact (*e.g.* Albuquerque *et al.*, 2021; Maqsoom *et al.*, 2020), or recommended DRASTIC modifications using the Stepwise Weight Assessment Ratio Analysis (SWARA) and employed the Entropy and Genetic Algorithm (GA) methods to adjust the relative weights of DRASTIC parameters (Torkashvand *et al.*, 2021).

Recently advanced methods based on AI, combining Multi Frameworks Technique (MFT) and Multi-Models Approach (MMA) are used. For instance, Nadiri *et al.* (2018a) introduced a two-stage learning process for the Basic DRASTIC framework, involving both unsupervised and supervised learning. At Stage 1, it has employed unsupervised learning methods, such as the Wilcoxon test (WDF) and Genetic Algorithm (BDF-GA), while at Stage 2, supervised learning by AI in Support Vector Machine (SVM) to run Multiple Frameworks (AIMF). Moreover, Nadiri *et al.* (2019) proposed a hierarchical approach involving the construction of multiple frameworks (MFs) and supervised learning from multiple models (MMs). Level 1 includes the development of MFs or MMs, while Level 2 encompasses the use of a model or algorithm to reuse outputs from Level 1 through four strategies, including a combination of MFs an d MMs. These studies, primary focused on the Standard DRASTIC Framework (SDF), didn´t consider the characteristics of fractured aquifer systems, particularly the parameter Fracture Media (Fr). In contrast, the proposed methodology integrates the Fr parameter into the Standard DRASTIC Framework, resulting in the modified DRASTIC-Fr. This approach evaluates the vulnerability of fractured aquifer system using AI by combining Multi Frameworks Technique (MFT) and Multi-Models Approach (MMA).

While widely accepted, the proposed method does have limitations, including issues related to low precision and high uncertainty in some cases of the thematic parameters and variables. In future research, it may be beneficial to employ various uncertainty estimation models to assess uncertainty in data layers and within the mathematical formulation, considering scoring system uncertainties. This integration of uncertainty estimation models can help on the uncertainties quantification in the Multi-Frameworks Techniques - SDF and FMF - and the Multi-Models Approach - GA and GEP - across different learning stages, encompassing both within-model and between-model errors.

6. Conclusions

Groundwater vulnerability mapping is a valuable tool for various purposes such as water protection, water resource management, and land-use planning. In this study, raster analysis within a Geographic Information System was employed to generate intrinsic vulnerability maps and respectively hydrogeological analysis.

The study introduces DRASTIC-Fr, a modified technique for mapping the Aquifer Vulnerability Index (AVI) in fractured system aquifers. This method incorporates a new thematic layer focusing on rock fractures, evaluating their hydraulic impact and potential for facilitating pollutant movement into the subsurface. The inclusion of the Fracture Media (Fr) parameter provides valuable insights into areas near geological extensions and tectonized formations. Despite potential dataset limitations, the study showcases the reliability of findings through unsupervised and supervised learning methods, emphasizing the robustness of the proposed methodology across two stages of multi-frameworks and multi-models. While acknowledging previous AI-based approaches, the uniqueness of DRASTIC-Fr lies in integrating Fr into the Standard DRASTIC Framework.The study acknowledges limitations, suggesting the incorporation of uncertainty estimation models for a more comprehensive understanding of uncertainties in data layers and mathematical formulations in future research, enhancing the method's applicability.

Groundwater vulnerability maps have several applications, such as a tool to delineate groundwater protection areas and identification of groundwater management. Additionally, the vulnerability map can guide the design of groundwater monitoring networks, helping to ensure the ongoing protection of local and regional groundwater resources. Furthermore, groundwater vulnerability is crucial for managing global challenges and planning sustainable resources management, safeguarding the region's residents and ecosystems, and promoting responsible resources management and sustainable development.

Acknowledgments

The authors are grateful to the staff of Applied Hydrosciences Laboratory for their effort and support during laboratory analysis. This research was developed under the FCT – Fundação para a Ciência e a Tecnologia, I.P. program, through the project´s reference UIDB/04683/2020 and UIDP/04683/2020.

References

Abdelkarim, B., Telahigue, F., Agoubi, B., 2022. Assessing and delineation of groundwater recharge areas in coastal arid area southern Tunisia. *Groundwater for Sustainable Development*, **18**: 100760.

Abdelkarim B, Antunes I. M. H. R, Agoubi, B., 2023a. Spatial variation of groundwater vulnerability to nitrate pollution in semi-arid area. *Atas XI Congresso Nacional de Geologia*, Coimbra.

Abdelkarim, B., Antunes, I. M. H. R., Abaab, N., Agoubi, B., 2023b. Modeling groundwater recharge mechanisms in semi-arid regions: integration of hydrochemical and isotopic data. *Euro-Mediterranean Journal for Environmental Integration*, **8**: 893-905.

Abdelkarim B, Antunes I. M. H. R., Abaab N, Tounekti A, Agoubi, B., 2023c. Assessment of groundwater vulnerability of fractured aquifers from arid regions. *Atas XI Congresso Nacional de Geologia*, Coimbra.

Abdelkarim, B., Telahigue, F., Abaab, N., Boudabra, B., Agoubi, B., 2023d. AHP and GIS for assessment of groundwater suitability for irrigation purpose in coastal-arid zone: Gabes region, southeastern Tunisia. *Environmental Science and Pollution Research*, **30**(6): 15422-15437.

Agoubi, B., 2018. Assessing hydrothermal groundwater flow path using Kohonen's SOM, geochemical data, and groundwater temperature cooling trend. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-018-1525-1.

Albuquerque, T., Roque, N., Rodrigues, J., Antunes, I. M. H. R., Silva, C., 2021. Groundwater Vulnerability Assessment in the Naturtejo UNESCO Global Geopark, Portugal. In: Abrunhosa, M. *et al.* (Eds.), Advances in Geoethics and Groundwater Management: Theory and Practice for a Sustainable Development, 223-228. https://doi.org/10.1007/978-3-030-59320-9_46.

Aller, L., Bennet, T., Leher, J. H., Petty, R. J., Hackett, G., 1987. *DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeological settings*. EPA.

Antunes, I. M. H. R., Albuquerque, M. T. D., Oliveira, S. F., and Sanz-Lobón, G. L., 2018. Predictive scenarios for surface water quality simulation - A watershed case study. *Catena*, **170**: 283-289.

Bhering, A. P., Antunes, I. M. H. R., Marques, E., Paula, R. S., Silva, A. R. N., 2023. Hydrogeology of Karst and Metapelitic Domains of the Semi-Arid Vieira River Watershed (Brazil) — A Contribution to Groundwater Resource Management. *Water* , **15** : 1-18. https://doi.org/10.3390/w15112066.

Dlala, M., 1995. *Evolution géodynamique et tectonique superposées en Tunisie : implication sur l'évolution géodynamique récente et la sismicité*. Thèse En Sciences Géologique. Université de Tunis El Manar II.

Foster, S. S. D., 1987. *Fundamental Concepts in Aquifer Vulnerability, Pollution Risk and Protection Strategy. In Vulnerability of Soil and Groundwater to Pollutants*. TNO Committee on Hydrological Research, 69–86.

Jang, W. S., Engel, B., Harbor, J., Theller, L., 2017. Aquifer vulnerability assessment for sustainable groundwater management using DRASTIC. Water, **9**(10): 792.

Maqsoom, A., Aslam, B., Khalil, U., Ghorbanzadeh, O., Ashraf, H., Faisal Tufail, R., Farooq, D., Blaschke T., 2020. A GIS-based DRASTIC model and an adjusted DRASTIC model (DRASTICA) for groundwater susceptibility assessment along the China–Pakistan economic corridor (CPEC) Route. Journal of Geo-Information, **9**(5): 332.

Missaoui, R., Abdelkarim, B., Ncibi, K., Hamed, Y., Choura, A., Essalami, L., 2022. Assessment of groundwater vulnerability to nitrate contamination using an improved model in the Regueb Basin, Central Tunisia. *Water, Air, & Soil Pollution*, **233**(8): 320.

Missaoui, R., Abdelkarim, B., Ncibi, K., Gentilucci, M., Brahmi, S., Ayadi, Y., Hamed, Y., 2023a. Mapping groundwater recharge potential zones in arid region using remote sensing and GIS perspective, Central Tunisia. Euro-Mediterranean Journal for Environmental Integration, **8**(3): 557-571.

Missaoui, R., Ncibi, K., Abdelkarim, B., Bouajila, A., Choura, A., Hamdi, M., Hamed, Y., 2023b. Assessment of hydrogeochemical characteristics of groundwater: link of AHP and PCA methods using a GIS approach in a semi-arid region, Central Tunisia. *Euro-Mediterranean Journal for Environmental Integration*, **8**(1): 99-114.

Msaddek, M. H., *et al.*, 2016. Fractures network analysis and interpretation in carbonate rocks using a multi-criteria statistical approach. Case study of Jebal Chamsi and Jebal Belkhir, south-western part of Tunisia. *Journal of African Earth Sciences*, **123**: 99–109.

Nadiri, A. A., Gharekhani, M., Khatibi, R., 2018a. Mapping aquifer vulnerability indices using artificial intelligence-running multiple frameworks (AIMF) with supervised and unsupervised learning. *Water Resour. Manage*. **32**(9): 3023–3040.

Nadiri, A. A., Sedghi, Z., Khatibi, R., Sadeghfam, S., 2018b. Mapping specific vulnerability of multiple confined and unconfined aquifers by using artificial intelligence to learn from multiple DRASTIC frameworks. *J. Environ. Manage*ment, **227**: 415–428.

Nadiri, A.A., Norouzi, H., Khatibi, R., Gharekhani, M., 2019. Groundwater DRASTIC vulnerability mapping by unsupervised and supervised techniques using a modelling strategy in two levels. *J. Hydrol*., **574**: 744–759.

Stempvoort, D. Van, Conklin, M. H., Novakowski, K. S., 1993. Hydrogeological Analysis of a Large-Scale Simulation of Borden Soil Aquifer Treatment (SAT) Project. *Water Quality Research Journal of Canada*, **28**(4): 665–674.

Torkashvand, M., Neshat, A., Javadi, S., Yousefi, H., 2021. DRASTIC framework improvement using stepwise weight assessment ratio analysis (SWARA) and combination of genetic algorithm and entropy. *Environ. Sci. Pollut. Res. Int*. **28**(34): 46704–46724.

Zargouni, F., 1985. *Tectonics of the Southern Atlas of Tunisia. Geometric and kinematic evolution of structures in shear zones*. Thesis in Sciences. Louis Pasteur University, Strasbourg.