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Integrating Geochemical and Regression Analyses to Increase Understanding of Groundwater Evolution in a Semiarid Basin: A Systematic Review

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Abstract: Hydrogeochemical evolution of groundwater in semiarid basins is influenced by complex interactions between natural processes (mineral weathering, dissolution-precipitation, ion exchange and evaporation) and human activities, including intensive abstraction and land use changes. This review synthesises evidence from thirteen (13) peer-reviewed studies that integrate geochemical modelling and regression or multivariate statistical analyses to deepen understanding of these dynamics. A PRISMA-based systematic search identified studies employing tools such as PHREEQC, NETPATH, isotopic modelling, multiple regression and PCA. Results highlight dominant processes including carbonate and silicate weathering, evaporite dissolution and anthropogenic modification of hydrochemical pathways. Regression and statistical approaches provided predictive insights, with models demonstrating robust explanatory power (e.g., R^2 >0.9 in some basins). Spatiotemporal trends revealed zonation, recharge dynamics and salinisation risks under semiarid conditions. The integration of geochemical and regression methods enhances predictive capacity and supports adaptive, evidence-based groundwater management frameworks essential for resilience under climate variability.

Keywords: Groundwater evolution; Semiarid Basin, Geochemical Modelling, Regression analysis, and Hydrogeochemistry

1. Introduction

Understanding the evolution of groundwater in semiarid regions is essential for sustainable water resources management, especially under increasing pressure from climate variability and anthropogenic use [1, 2]. Groundwater composition is defined by various processes, e.g., mineral precipitation/dissolution, evaporation, weathering, recharge dynamics and human impacts. Geochemical modelling elucidates these mechanisms, though regression and multivariate analyses establish predictive relationships between hydrochemical parameters [3, 4]. This review synthesises 13 peer-reviewed articles that integrate geochemical modelling and/or regression analysis-based statistical analyses to dissect groundwater evolution in semiarid contexts. It addresses: (i) the dominant hydrogeochemical processes identified, (ii) how regression or statistical models quantify relationships, (iii) insights into spatiotemporal groundwater chemistry changes and (iv) implications for management under semiarid conditions. The aim is to spotlight methodological integration, reveal common themes and propose future directions for a holistic understanding of groundwater evolution.

Groundwater in semiarid regions is increasingly threatened by declining recharge, over extraction and pollution, yet its evolutionary pathways remain complex due to the interplay of anthropogenic and natural processes [5, 6]. Traditional hydrochemical assessments offer useful snapshots but often fall short in unravelling the coupled mechanisms and long-term dynamics influencing groundwater composition. Geochemical modelling offers a mechanistic understanding of mineral-water interactions, while regression and multivariate analyses reveal statistically significant patterns and predictive relationships between hydrochemical parameters [7, 8]. Integrating these approaches is therefore critical for moving beyond descriptive assessments toward holistic interpretations of groundwater evolution. Despite growing applications, there remains a lack of consolidated knowledge on how these methods complement each

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other in semiarid contexts. This review fills that gap by synthesising evidence from 13 peer-reviewed studies and offering a methodological and conceptual framework to guide sustainable water resource management and policy formation in vulnerable semiarid basins.

2. METHODOLOGY (PRISMA Framework)

A PRISMA-style systematic search was performed across databases, e.g., WoS, Scopus, MDPI, PubMed, and SpringerLink. Search term included 'geochemical modelling groundwater semiarid', 'regression analysis groundwater chemistry', 'groundwater evolution semiarid basin geochemical', etc. Inclusion criteria: (i) empirical studies in semiarid or arid basins, (ii) incorporating geochemical modelling (e.g., PHREEQC, NETPATH, saturation indices), (iii) employing statistical or regression techniques (MRA, PCA, Multivariate Analysis), published in peer-reviewed journals between 2015 and 2025. Thus, from an initial set of forty (40), thirteen (13) studies met criteria (Figure 1). These were categorised and extracted for the key study area, methods, main geochemical drivers' statistical models and findings.

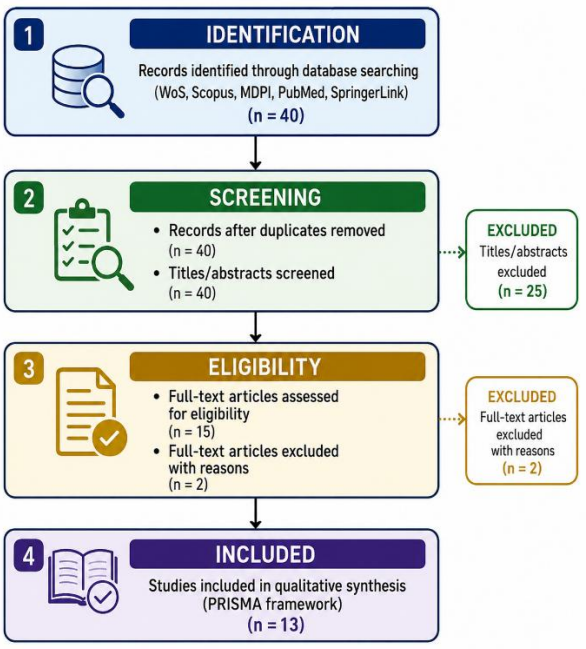

Fig.1- PRISMA flow chart

3. Results and Discussion

3.1. Dominant Geochemical Processes

Based on the summarised studies, groundwater evolution in semiarid basins is controlled by (i) weathering and mineral dissolution (carbonate, silicate, evaporite minerals)- such as Ghar Boumaaza (carbonate dissolution) [9],[10]; Kaduna Basin (Silicate weathering) [11]; Longwanggou (dissolution of halite and gypsum) [10], (ii) Ion exchange mechanisms [12], zoning of hydrochemical evolution, and (iii) recharge origin and mixing, such as isotopic insights in Qaidam and Sulaimani basins.

3.2. Regression and statistical modelling

Regression modelling was performed in Algeria's Ghar Boumaaza, using a third-degree polynomial regression model relating TDS to discharge (Q), yielding a predictive accuracy ($R^2 = 0.95$) [9]. In the Kaduna basin, multiple regression analysis (MRA) tied hydrochemical variation to rock-weathering processes (Na+/Cl- ratios), with statistical significance (R-Sq 63%, $p<0.01$)[11]. Multivariate statistical applications (PCA, cluster analysis, factor analysis) in the Ghana Pru Basin, Northern Ethiopia, and the Great Artesian Basin were used to classify water types and interpret controlling processes [13, 14]. Zoning approaches used in the Western Jilin Model, hydrochemical zoning coupled with PHREEQC modelling, distinguish recharge – runoff-discharge zones (Figure 2).

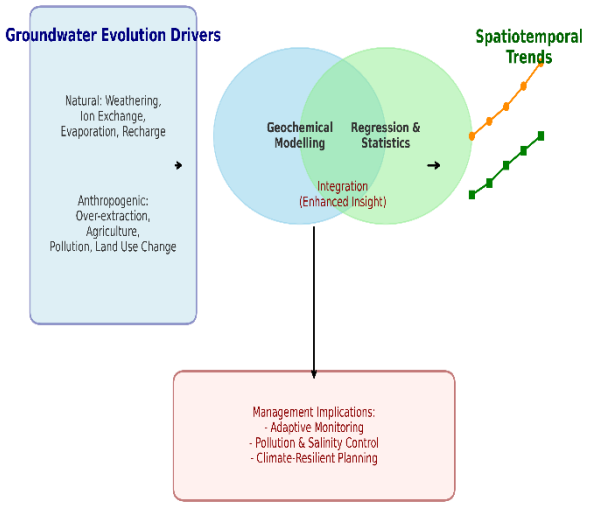

Fig.2-Integrating geochemical and regression analyses

The reviewed studies show that groundwater evolution in semiarid basins can be better understood if geochemical modelling is coupled with regression and multivariate statistical methods. Geochemical modelling techniques, such as PHREEQC, NETPATH, saturation index evaluation, isotopic modelling, and hydrochemical facies analysis, explain mineral dissolution, ion exchange, evaporation, recharge processes, and the interaction between groundwater and rock in a mechanistic way [1, 2]. Nonetheless, these methods are much more powerful when complemented by statistical and regression analyses that can quantify the relationships among hydrochemical variables and determine the most important controlling factors.

A few studies demonstrated improvements in the predictive interpretation of groundwater systems through regression analysis. In the Ghar Boumaaza region (Algeria) [3], third-order polynomial regression showed a strong correlation with groundwater discharge and very high predictive precision (R2 = 0.953). This illustrates the ability of regression models to predict the

hydrochemical evolution with different hydrological conditions. Likewise, the Kaduna Basin study used Multiple regression analysis (MRA) to assess the effects of silicate weathering and ionic relationships on groundwater chemistry and obtained statistically significant results: $R2 = 0.63$, $p < 0.01$ [4]. These models can enhance understanding of the quantitative impact of lithological and hydrogeochemical processes on groundwater composition.

Data dimensionality reduction and identification of the controlling hydrochemical processes for groundwater evolution were widely adopted in the reviewed studies, using multivariate statistical techniques such as Principal Component Analysis (PCA), Factor Analysis (FA) and Cluster Analysis (CA). PCA and factor analysis successfully separated natural geogenic processes from anthropogenic processes in the Pru Basin (Ghana) [5], Northern Ethiopia, and the Great Artesian Basin (Australia), and cluster analysis classified groundwater samples based on hydrochemical similarities and evolution. These methods are particularly useful in semiarid basins, where hydrochemical data tend to be more complex due to several interacting environmental factors.

Groundwater dynamics were also interpreted using spatially integrated approaches, namely GIS-based vulnerability modelling and hydrochemical zoning. The Wadi Fatimah study exemplifies the use of a NETPATH modelling approach in conjunction with a DRASTIC-GIS analysis to demarcate vulnerable groundwater areas affected by evaporation and ion-exchange processes (El Osta et al. [1]). Similarly, hydrochemical zoning models in Western Jilin showed that recharge areas, runoff areas, and discharge areas were located along groundwater flow paths and were associated with geochemical reactions [2]. Similarly, in Western Jilin, recharge, runoff, and discharge zones were found to align with groundwater flow paths and to be linked to geochemical reactions within hydrochemical zonings.
The literature reviewed thus indicates that the use of mechanistic geochemical models in association with regression, multivariate statistics, and spatial analysis frameworks will improve predictive capability and hydrochemical classification, and strengthen groundwater management decision-making in semiarid regions. The methodological integration helps move from descriptive groundwater assessment to predictive, management-oriented hydrogeochemical modelling.

3.3. Integration Insights and Comparative Themes

The literature indicates transferable frameworks. For instance, the Ghar Boumaaza and Kaduna studies show that combining modelling with regression/statistical techniques enables both mechanistic understanding and predictive capacity [9, 11]. Likewise, zonal differentiation in multiple basins (Jilin, Ghana, Qaidam) revealed spatial hydrochemical variations along flow paths or recharge-discharge gradients. Additionally, anthropogenic/human influence in Haolebaoji and elsewhere underscores the overexploitation or land-use change, which accelerates chemically distinct evolutionary pathways [15]. The literature further elucidates recharge dynamics using isotopes in the Qaidam and Sulaimani basins, highlighting how isotopic data reveal Paleowater vs. modern recharge contributions (Figure 3).

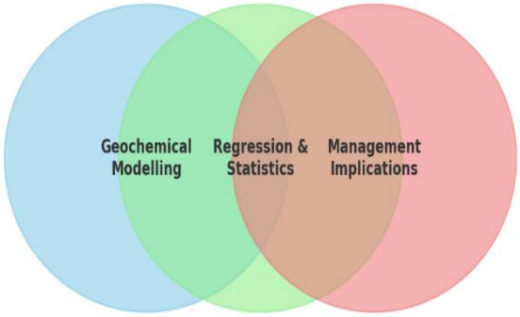

Fig.3 - Integration of methods for understanding groundwater evolution

The comparative study of the reviewed works shows that the integrated hydrogeochemical and statistical approaches have strong potential to better interpret the evolution pathways of groundwater in semiarid basins. The geochemical modelling tools (PHREEQC and NETPATH) provide mechanistic explanations of mineral dissolution, ion exchange, and evaporation processes, and regression and multivariate analyses assess the strength and significance of the hydrochemical relationships. The high predictive ability reported in Ghar Boumaaza ($R^2 = 0.95$) and the statistical significance of the multiple regression results obtained in the Kaduna Basin demonstrate that combining statistical approaches with geochemical modelling can improve predictive ability and process validation across different and contrasting hydrogeological settings.

Another significant comparative theme is the spatial variability of groundwater chemistry along recharge–discharge gradients. Progressive hydrochemical evolution in relation to lithology, groundwater residence time and evaporation intensity was observed in studies conducted in Western Jilin, Ghana and the Great Artesian Basin. All of the above techniques confirmed a systematic change in groundwater chemistry from bicarbonate facies associated with recharge to more saline Na–Cl or mixed groundwater facies in discharge areas.

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Table 1. Literature Summary

S/N	Region/Country	Geochemical Methods	Regression/Statistical Analysis	Major Results	References
1	Ghar Boumaaza, Algeria	Hydrochemical facies, PCA, 3rd – Degree Polynomial Regression (TDS vs Q)	Polynomial regression	Carbonate Dissolution Dominant; Very high R^2 =0.953, validated (MDPI)	Guettaia, et al. [9]
2	Kaduna Basin, Nigeria	Geochemical modelling (Mineral Stability), MRA	Multiple Regression Analysis, Na^+/Cl^- Ratio	Silicate Weathering Dominates; R-Sq=63%, p-value <0.01	Wali, et al. [11]
3	Qaidam Basin, NW China	Hydrogeochemical and isotopic Modelling, Numerical Flow	Numerical Modelling (Flow Systems Classification)	Multiple flow systems; mineral dissolution/weathering control chemistry	Wang, et al. [16]
4	Wadi Fatimah, Saudi Arabia	NETHPATH geochemical Modelling, DRASTIC Vulnerability	GIS-based vulnerability modelling	Evaporation and ion exchange key; vulnerability zoned	El Osta, et al. [12]
5	Western Jilin, China	PHREEQC reverse simulation, hydrogeochemical zoning model.	Zoning model (no regression)	Evolution through lixiviation→cation exchange→ evaporation zonation	Li, et al. [17]
6	Pru Basin, Ghana	Ionic ratios, multivariate statistics, geochemical modelling	Multivariate statistical methods	Evolution of water types from Na-HCO_3 to diverse facies	Ganyaglo, et al. [13]
7	Great Artesian Basin, Australia	Multivariate Stats+3D geological model	PCA, Cluster Analysis, Factor Analysis	Evapotranspiration-driven Na-Cl evolution along flow paths	Moya, et al. [18]
8	Sulaimani-Warmawa, Iraq	Hydrogeochemical Modelling + Isotopic Modelling	Isotope data interpretive (no regression	Transition from Ca-HCO_3 to Ca-Mg-HCO_3; dissolution of halite/gypsum	Mahmmud, et al. [19]
9	Djelfa, Algeria	Geochemical Assessment, Stable Isotopes	Descriptive analysis (no Regression)	Evaporation/Mineralisation processes in a Multilayer aquifer	Ali Rahmani and Chibane [20]
10	Haolebaoji, Ordos Basin, China	Gibbs, Saturation Index, PCA	Principal factor analysis	Human exploitation is shifting the trajectories of hydrochemical evolution.	Zhang, et al. [15]
11	Northern, Ethiopia	Geospatial and Multivariate Statistics	Multivariate Statistical Analysis	Identified sources controlling groundwater chemistry using GIS overlay	Tesfaye [14]
12	Yola, Nigeria	Geochemical ionic ratios	Ion ratio analysis, descriptive	Silicate weathering is dominant; water types vary by depth	Obiefuna and Orazulike [21]
13	Longwanggou (Ordos Basin coal mine)	PHREEQC inverse geochemical modelling	Ion ratios, saturation indices	Leaching and cation exchange; dissolution of evaporites/carbonates.	Lu, et al. [10]

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This spatial structure provides a strong foundation for vulnerability assessment and groundwater resource planning in semiarid regions.

Moreover, the literature reviewed indicates a significant anthropogenic impact on groundwater evolution. The hydrogeochemical pathways of natural ecosystems are being altered by intensive abstraction, agricultural activities, mining operations, and land-use changes, especially in vulnerable semiarid aquifers. The study in the Ordos Basin and Wadi Fatimah suggests that groundwater may be more prone to deterioration in quality from human activities than from natural geochemical processes. The combination of geochemical modelling, predictive statistical and spatial analyses provides a more holistic approach to sustainable groundwater monitoring, risk assessment and adaptive water-resource management.

3.4. Methodological reflections

Most studies effectively couple geochemical modelling (saturation indices, mineral equilibria, thermodynamic modelling) with statistical or regression analysis, which improves both quantification and explanation. Regression models (e.g., polynomial MRA) offer tangible predictive and validation capabilities, but they are less common than descriptive multivariate techniques [22]. Spatial tools (GIS, zoning models) are increasingly important for mapping vulnerability (e.g., Wadi Fatimah) and Hydrochemical differentiation [12]. Few studies link directly statistical predictors to management outcomes; future research could prioritise actionable modelling.

4. Conclusion

This review brought together data from 13 peer-reviewed studies to show that the evolution of groundwater in semiarid basins is driven by complex natural and anthropogenic factors, including mineral weathering, evaporite dissolution, ion exchange, evaporation, recharge dynamics, and intensive abstraction. Geochemical modelling, isotopic analysis, regression, and multivariate statistics were integrated to better explain hydrochemical processes and increase predictive skill; this was achieved consistently. The reviewed studies also identified significant differences in groundwater chemistry across recharge–discharge zones, and that zoning and GIS approaches can help identify vulnerability patterns and hydrochemical differentiation.

Although this review summarises only thirteen (13) peer-reviewed studies, it reveals:

i. Geochemical drivers of groundwater evolution (mineral dissolution, weathering, evaporation and ion exchange are consistently pivotal in semiarid groundwater composition.
ii. Modelling integration, which combines geochemical modelling with regression/statistical methods (e.g., polynomial regression, MRA, PCA), deepens mechanistic insight and predictive power.
iii. Spatial variability in hydrochemical evolution shows zonation influenced by geological conditions and hydrodynamics; GIS-based zoning models effectively capture this.
iv. Recharge characterisation using isotopic and modelling approaches clarifies the sources and timing of groundwater recharge.
v. Human impacts, through intensive abstraction and land-use change, significantly alter geochemical evolution paths.

4.1. Recommendations and future research direction

i. Expand regression-based modelling to integrate with geochemical modelling, for example, multivariate regression predicting major hydrochemical parameters based on land use, recharge and climate parameters.
ii. Longitudinal monitoring to evaluate temporal changes, particularly under exploitation or climate change.
iii. Comparative cross-basin studies to benchmark semiarid aquifers' behaviour and modelling techniques
iv. Decision-support integration via developing frameworks that link hydrochemical modelling outputs to actionable water management strategies.
v. Leveraging machine learning (e.g., GP-DNN) for improved prediction in data-sparse settings; mostly applied to levels, these approaches extend to chemistry.

Therefore, integrating geochemical modelling with regression and statistical techniques offers a robust, multidisciplinary framework for unravelling groundwater evolution in semiarid basins. The studies reviewed here show both scientific insight and practical potential. Hence, future work should build on this synergy toward predictive, spatially resolved and management-oriented groundwater chemistry modelling.

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References

[1] M. Deshmukh, A. Elbeltagi, and S. Kouadri, "Climate change impact on groundwater resources in semiarid regions," in *Climate Change Impact on Groundwater Resources: Human Health Risk Assessment in Arid and Semiarid Regions*: Springer, 2022, pp. 9-23.

[2] K. Priyan, "Issues and challenges of groundwater and surface water management in semiarid regions," *Groundwater resources development and planning in the semiarid region,* pp. 1-17, 2021.

[3] D. Driba and L. E. Beckingham, "Unraveling hydrogen-induced geochemical reaction mechanisms through coupled geochemical modeling and machine learning," *Applied Geochemistry,* vol. 183, p. 106330, 2025.

[4] N. Liu, M. Chen, D. Gao, Y. Wu, and X. Wang, "Identification of hydrogeochemical processes in shallow groundwater using multivariate statistical analysis and inverse geochemical modeling," *Environmental Monitoring and Assessment,* vol. 197, no. 2, p. 135, 2025.

[5] S. Fuqaha, "Global trends and research frontiers of water harvesting and groundwater recharge: A comprehensive bibliometric review," *Oppor Chall. Sustain,* vol. 4, no. 2, pp. 110-134, 2025.

[6] A. Ali and M. Bilal, "A comprehensive review of GIS and remote sensing applications in assessing land use and land cover impacts on groundwater systems," *Environmental Science and Pollution Research,* pp. 1-22, 2025.

[7] X. Qin *et al.*, "Multivariate Statistics and Hydrochemistry Combined to Reveal the Factors Affecting Shallow Groundwater Evolution in a Typical Area of the Huaibei Plain, China," *Water,* vol. 17, no. 7, p. 962, 2025.

[8] R. Abdelouahab *et al.*, "Geochemical and isotopic relationships between groundwater and rainwater in the Zaccar karst system (Northern Algeria)," *Sustainable Water Resources Management,* vol. 11, no. 3, pp. 1-19, 2025.

[9] S. Guettaia *et al.*, "Hydrochemical Characterization and Predictive Modeling of Groundwater Quality in Karst Aquifers Under Semiarid Climate: A Case Study of Ghar Boumaaza, Algeria," *Sustainability*, vol. 17, no. 15*,* doi: 10.3390/su17156883.

[10] C. Lu *et al.*, "Study on inverse geochemical modeling of hydrochemical characteristics and genesis of groundwater system in coal mine area - a case study of Longwanggou Coal Mine in Ordos Basin," (in eng), *Environ Sci Pollut Res Int,* vol. 31, no. 11, pp. 16583-16600, Mar 2024, doi: 10.1007/s11356-024-32153-z.

[11] S. U. Wali *et al.*, "Geochemical and Regression Analyses of Shallow Groundwater Evolution in a Semiarid Basin," *Available at SSRN 5264086,* 2025.

[12] M. El Osta, B. Niyazi, and M. Masoud, "Groundwater evolution and vulnerability in semiarid regions using modeling and GIS tools for sustainable development: Case study of Wadi Fatimah, Saudi Arabia," *Environmental Earth Sciences,* vol. 81, no. 9, p. 248, 2022.

[13] S. Y. Ganyaglo *et al.*, "Groundwater geochemical evolution, origin and quality in the Lower Pra Basin, Ghana: insights from hydrogeochemistry, multivariate statistical analysis, mineral saturation indices, stable isotopes (δ2H and δ18O) and geostatistical analysis," *Acta Geochimica,* vol. 44, no. 2, pp. 348-372, 2025.

[14] A. T. Tesfaye, "Integrated GIS, remote sensing, and analytical hierarchical process approaches to delineate groundwater storage zones in the Sub-Saharan region of Northern Ethiopia," *Heliyon,* vol. 11, no. 10, 2025.

[15] B. Zhang, R. Zhang, P.-F. Han, J. Wang, and L. Wan, "Evolution of Hydrogeochemistry in the Haolebaojinao Watershed of the Ordos Basin, China," *Sustainability*, vol. 15, no. 6*,* doi: 10.3390/su15065091.

[16] J. Wang *et al.*, "Hydrogeochemical sources and enrichment mechanisms of trace elements in river water of a typical endorheic headwater region on Tibetan Plateau," *Applied Water Science,* vol. 15, no. 9, pp. 1-18, 2025.

[17] C. Li, J. Fang, F. Feng, T. Yao, Y. Shan, and W. Su, "Differential Evolution in Hydrochemical Characteristics Amongst Porous, Fissured and Karst Aquifers in China," *Hydrology,* vol. 12, no. 7, p. 175, 2025.

[18] C. E. Moya, M. Raiber, M. Taulis, and M. E. Cox, "Hydrochemical evolution and groundwater flow processes in the Galilee and Eromanga basins, Great Artesian Basin, Australia: a multivariate statistical approach," *Science of the Total Environment,* vol. 508, pp. 411-426, 2015.

[19] R. Mahmmud, O. Sracek, O. Mustafa, B. Čejková, I. Jačková, and L. Vondrovicová, "Groundwater geochemistry evolution and geogenic contaminants in the Sulaimani-Warmawa Sub-basin, Sulaimani, Kurdistan Region, Iraq," *Environmental Monitoring and Assessment,* vol. 194, no. 5, p. 352, 2022.

[20] S. E. Ali Rahmani and B. Chibane, "Geochemical assessment of groundwater in semiarid area, case study of the multilayer aquifer in Djelfa, Algeria," *Applied Water Science,* vol. 12, no. 4, p. 59, 2022.

[21] G. I. Obiefuna and D. M. Orazulike, "The hydrochemical characteristics and evolution of groundwater in semiarid Yola Area, Northeast, Nigeria," *Research Journal of Environmental*

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and Earth Sciences, vol. 3, no. 4, pp. 400-416, 2011.

[22] D. Mikšová, "Advanced statistical methods for geochemical mineral exploration," Technische universität Wien, 2020.