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Comparative assessment of groundwater quality challenges confronting Mediterranean coastal aquifers: A synoptic review

Sara Bouhout[1,2], *Khadija* Haboubi[2], *Yahya* El Hammoudani[2], *Chaimae* Haboubi[2], *Aouatif* El Abdouni[1,2], *Mohamed Salahdine* Elyoubi[1], *Fouad* Dimane[2]

[1] Laboratory of Organic Chemistry, Catalysis and Environment, Faculty of Science, Ibn Tofail University, Kénitra, Morocco
[2] Laboratory of Engineering Sciences and Application, National School of Applied Sciences - Al Hoceima, Abdelmalek Essaadi University, Morocco

Abstract. Coastal aquifers, essential for agriculture, domestic, and industrial water supply, face significant sustainability challenges, particularly in Mediterranean regions, due to the adverse effects of human activities, climatic threats, and natural geological conditions causing salinization. This paper synthesizes findings from studies on three Mediterranean coastal aquifers— the Pleistocene aquifer in the Gaza Strip, the karstic aquifer in Bokkoya, and the Mio-Plio-Quaternary aquifer in Djeffara of Medenine—highlighting the escalating deterioration due to over-exploitation and arid conditions. It compares the methodologies used in these studies, such as statistical analysis, geostatistical modeling, and groundwater quality indices, to assess groundwater quality and address salinization challenges. This review aims to identify methodological limitations and propose strategies to fill research gaps, particularly in combating seawater intrusion, to enhance the sustainable management of these critical water resources.

1. Introduction

Groundwater serves as a crucial freshwater resource globally, with its significance magnified in the Mediterranean Basin—one of the world's warmest and driest areas. This region faces water scarcity, marked by uneven distribution and temporal variability, exacerbated by climate-induced reductions in rainfall and increased evaporation [1]. The Mediterranean, especially its semi-arid locales, experiences significant stress on groundwater resources due to heavy demand from growing populations and tourism, leading to extensive extraction and a notable drop in water levels [2], [3], [4], [5], [6].

This overuse not only threatens to intensify salinization through the inland movement of the freshwater-seawater interface but also faces challenges from various pollution sources [7], [8], [9]. Salinization is aggravated by the confluence of natural processes, such as the dissolution of evaporite minerals and the mobilization of ancient seawater, and human activities, including agricultural runoff, urban effluents, and industrial discharges. Together, these factors contribute to the complex issue of groundwater quality degradation, underscoring the need for comprehensive management and protection strategies [10], [11].

Facing these multifaceted pressures on groundwater resources, researchers in the Mediterranean basin have employed hydrochemical methods to investigate the nuanced interactions among various processes affecting groundwater quality, marking this as a captivating area of study [12], [13], [14]. These inquiries, often meticulous and enlightening, tend to concentrate on isolated instances, which, while valuable, limit broader understanding. Contrastingly, comprehensive comparative studies that examine groundwater's chemical attributes across multiple coastal aquifers in the region are relatively rare [15], [16], [17], [18], [19], [20].

When such studies do exist, they frequently narrow their focus to particular geochemical processes, thereby omitting a holistic view of the factors influencing groundwater salinity and quality. This gap underscores the necessity for more integrated research approaches [21]. By broadening the scope to include multiple aquifers and a wider array of influencing factors, future studies could offer deeper insights into the regional patterns of groundwater chemistry, enhancing our understanding of salinization dynamics and informing more effective management and conservation strategies across the Mediterranean's diverse coastal ecosystems [22].

Therefore, the objective of this review is twofold: firstly, to offer a concise overview of current methodologies for analyzing salinization patterns and chemical characteristics of groundwater; and secondly, to present a comparative analysis of the techniques used to examine changes in chemical compositions within groundwater across three chosen Mediterranean aquifers.

2. Overview on techniques for tracing salinity sources in aquifers

Indeed, the issue of groundwater salinization in Mediterranean locations has captured the interest of numerous researchers. Observing the chart below, it becomes apparent that publications addressing the chemical condition of groundwater have been increasing exponentially since 2005.

Table 1. Common methods used for groundwater quality evaluation (modified from [23])

Groundwater quality assessment approaches				
Graphical techniques	Statistical techniques	Techniques applied in GIS	Techniques based on Artificial Intelligence	Geochemical modeling
Collins diagram Radial/vector diagram Stiff diagram Pie/circular charts Langelier-Ludwig diagram Piper diagram Schoeller diagram Durov diagram Giggenbach triangle USSL diagram Wilcox diagram Gibbs diagram	Time series plots -scatter plots, line plots, areal plots, bar plots) Histogram/Frequency plots Box & Whisker plot Cumulative Matrix Analysis of variance Student's t-test Time series analysis -trend, homogeneity, stationarity, periodicity, persistence, stochasticity- Multivariate statistical techniques Principal component analysis Cluster analysis Discriminant analysis Canonical correlation analysis Partial least squares modeling Correspondence analysis	Remote sensing approach Geostatistical modeling Groundwater Quality Index Seawater Mixing Index	Genetic Algorithm Artificial Neural Network Fuzzy Logic Neuro- Fuzzy Multi-criteria decision making Support Vector Machine	Inverse Modeling Speciation Modeling Mass Balance Modeling BALANCE NETPATH Forward Modeling Reaction-Path Reaction-Transport MINTEQ PHREEQE

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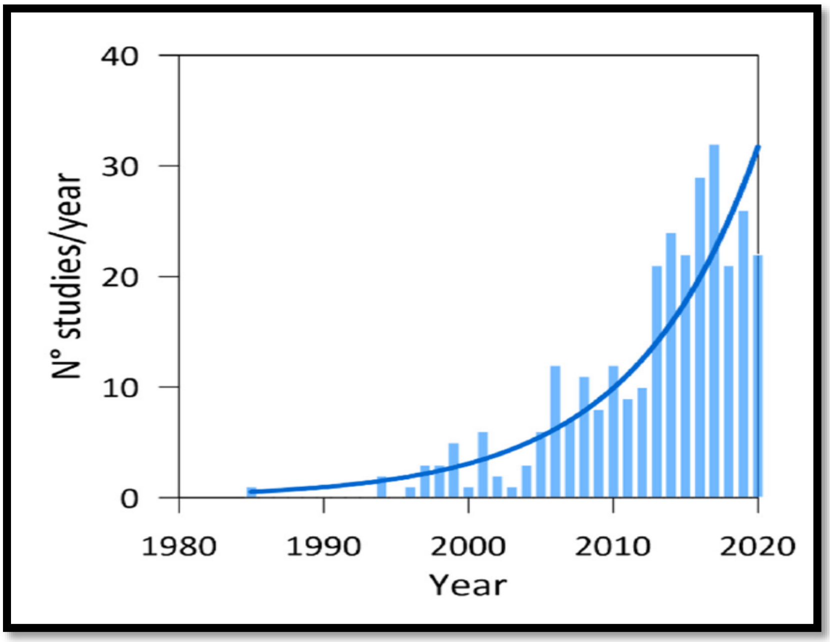

Fig. 1. Studies focusing on chemical state of groundwater in Mediterranean countries (modified from [24]).

The table presented offers a methodical summary of the techniques researchers employ to investigate and interpret hydrochemical data, highlighting the importance of these diverse methodologies in identifying both natural and human-made influences on groundwater's chemical makeup. This arsenal of methods spans from traditional graphical representations to cutting-edge statistical analyses and artificial intelligence (AI) applications, each playing a pivotal role in the nuanced examination of water quality.

Particularly in the Mediterranean basin, and notably within North African territories, recent studies have frequently utilized geochemical assessments, statistics-based techniques, and indices specific to seawater intrusion. Literature indicates that while classic graphical approaches offer a straightforward preliminary assessment of water quality, they fall short in their capacity to account for neutral chemical elements, focusing primarily on the contribution of major ions. This inherent limitation underscores the necessity for statistical analyses in hydrochemical studies. Such statistical techniques, by embracing a broader array of chemical and physical parameters, enhance the analysis, thereby addressing the deficiencies inherent in solely graphical methodologies [25].

Furthermore, the integration of study findings into Geographic Information System (GIS) software substantially improves the ease and accuracy of data interpretation, facilitating a more dependable understanding of water quality issues. Beyond refining current methods, there's a pressing need to tailor these approaches to the unique characteristics of each study area. In this vein, AI-driven computational techniques are increasingly advocated for tackling the complexities of water quality evaluation and mapping its spatial variations across extensive areas. This evolution towards more sophisticated analytical tools promises to enrich our comprehension of groundwater quality dynamics, making strides toward more informed and effective water management strategies [26], [27].

Table 2. Conveniences and drawbacks of the widely-used techniques in evaluating groundwater quality

Advantages	**Restraining factors**
Graphical methods enable rapid visualization	Graphical displays incorporate few chemical constituents into the analysis
Statistical tools are suitable for simultaneous analysis of a great number of observations	Statistical approaches require large amount of data to produce reliable results
GIS tool is effective for solving problems where large volumes of data vary in spatial extent	GIS-based methods are established subjectively
AI methods have the ability to model nonlinear and complicated phenomena without prior understanding of underlying mechanisms	High cost for AI model development (hardware/ software/algorithms)

3. Summary and comparative snapshot of 3 case studies

In this segment, we delve into an analytical overview of findings from three seminal studies on aquifers that are contaminated within distinct regions: the Gaza Strip in Palestine, Djeffara of Medenine in Tunisia, and the Bokkoya massif in Morocco. These regions, located along the Mediterranean coast, share the challenge of intensive groundwater exploitation amidst semiarid climates, which has led to altered hydrological regimes [28], [29], [30].

The geological makeup of these areas plays a significant role in their water quality issues. Specifically, the Gaza Strip features calcareous sandstone interspersed with clay layers, while Djeffara's geology is characterized by an alluvial mix of sand, clay, and pebbles with variable thickness. In contrast, the Bokkoya aquifer is predominantly limestone with notable karstic formations.

The complexity and uniqueness of each aquifer's lithological and hydrological contexts necessitate a sophisticated approach to assess groundwater quality, contamination levels, and vulnerability. Researchers in these studies have employed a suite of integrated techniques to understand the multifaceted impacts of anthropogenic activities and natural geological changes on groundwater systems. These methods range from geochemical analyses to advanced hydrological modeling, aiming to capture the dynamic interactions between groundwater flow patterns and lithological heterogeneity over time.

By examining these factors in concert, the studies provide valuable insights into the processes driving contamination and vulnerability in these critical water resources, highlighting the need for tailored management and conservation strategies to safeguard them against further degradation. Through such detailed investigations, the scientific community gains a deeper understanding of the challenges and potential solutions for protecting groundwater quality in semiarid, heavily exploited coastal aquifers.

Table 3. Contribution and scope of different methods employed in the shortlisted articles

Study site	Adopted method	Novelty	Shortcomings
Gaza strip	Geochemical and Statistical techniques along with Geostatistical modelling	Supplying spatial information on groundwater quality considering the impact of underlying geology and coastal boundary	Geostatistical methods provide results with considerable smoothing effect
Bokkoya massif	**Groundwater quality indices** compared with **Richards** and **Wilcox** diagrams	Corroborating the results of GWQI by applying Wilcox and Riverside methods	Groundwater quality indices cannot be comparable when applied on different areas
Djeffara of Medenine	Groundwater quality index for seawater intrusion ($\mathbf{GQI_{SWI}}$) and **GALDIT model**	The application of a representative index specific to seawater intrusion for preliminary assessment	GQI(SWI) cannot fully illustrate the hydrogeochemical processes entailed by seawater intrusion In GALDIT framework, weights and rates are subjectively selected depending on experts.

4. Conclusion

Reflecting on the analyses conducted in this review, several key observations emerge regarding the assessment of groundwater systems, particularly in regions facing the dual challenges of contamination and over-exploitation. Firstly, it's apparent that each method used to study groundwater—from hydrochemical analyses to remote sensing and modeling techniques—carries its unique set of strengths and weaknesses. The choice of methodology should thus be strategically aligned with the specific characteristics of the groundwater system under study, including its geological context and the nature of the contaminants, as well as the availability and quality of data.

The integration of various investigative techniques, facilitated by tools such as Geographic Information Systems (GIS) or advanced statistical software, can significantly enhance our ability to understand and mitigate the limitations inherent to any single method. Such a multidisciplinary approach allows for a more comprehensive and nuanced analysis of groundwater quality and dynamics, enabling the identification of both natural and anthropogenic factors influencing aquifer systems.

Moreover, the resilience of porous aquifers to contamination and overuse is noteworthy; these systems tend to exhibit a greater capacity to absorb impacts compared to their less porous counterparts. However, this resilience is coupled with a caveat—the time required for these aquifers to naturally restore their equilibrium and quality is considerably longer. This underscores the importance of adopting proactive and preventative management strategies to protect groundwater resources over the long term.

The scope and depth of groundwater studies often correlate with the perceived economic value of the resource. Detailed investigations are predominantly conducted in areas where groundwater is deemed an essential asset for economic development, agriculture, or human consumption. This observation points to a gap in research and protection efforts in regions where groundwater's value, though significant, may not be immediately quantified in economic terms. Addressing this gap is crucial for ensuring the sustainable management of groundwater resources globally, emphasizing the need for a more equitable distribution of research attention and resources.

In summary, advancing our understanding and management of groundwater systems requires a careful selection of analytical methods, the strategic integration of diverse techniques, and a broad recognition of groundwater's intrinsic value. By embracing these principles, we can better protect this vital resource in the face of increasing environmental and anthropogenic pressures.

Conflict of interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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