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Groundwater Quality Monitoring in Response to Marine Intrusion: A Case Study in Northern Morocco

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Abstract. Water stress, resulting from a demand for water exceeding the available quantity, is a major global challenge. Groundwater usage is a commonly adopted strategy to address this situation, but it often leads to marine intrusion, threatening the quality of water in coastal aquifers. This phenomenon typically stems from overexploitation of aquifers, declining water table levels, and rising sea levels due to climate change. Our study aims to monitor the quality of groundwater intended for human consumption and provide a detailed assessment of its current state. We identified several physicochemical parameters, such as temperature, pH, and bicarbonates, with maximum electrical conductivity values reaching 2810 µs/cm, a total hardness of 21 meq/L, sulfate levels of 689 mg/L, and chloride levels of 628 mg/L, from six boreholes and one well located along the coastal area of the Al Hoceima region. These samples were also subjected to Principal component analysis (PCA) of the chemical parameters, revealing two factors that represent approximately 62.15% of the total variance in the groundwater quality dataset. Simulation results indicate signs of seawater intrusion in several areas, particularly near the coast, emphasizing the urgency of protecting groundwater resources and developing sustainable management strategies to ensure a safe and reliable supply of drinking water in the region.

Key words: Groundwater exploitation, Marine Intrusion, Principal Component Analysis

1 Introduction

The Al Hoceima region experienced a significant decline in its surface water resources due to drought periods in 2000, 2015, and 2023, impacting the exploitation of groundwater [1]. This decrease in groundwater recharge is a result of decreased precipitation and increased evapotranspiration, exerting additional pressure on these resources [2]. The quality of groundwater in this region is influenced by natural factors such as aquifer geology, as well as marine intrusion in coastal areas and aquifers resulting from intensive exploitation of groundwater resources [3,4]. This overexploitation can cause significant damage to ecosystems, populations, and local economies [3]. Several studies have been conducted to assess the quality of groundwater and the impact of marine intrusion in the Al Hoceima region. A study led by S. Bohout and colleagues revealed that groundwater in Ghiss-Nekor has high salinity, making it primarily suitable for irrigation due to its high concentration of total dissolved solids (TDS). Additionally, the presence of fine particles appears to limit marine intrusion in the northwest area[4].

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Another study, focusing on monitoring the physicochemical parameters of water sources in the coastal karstic aquifer of the Bokkoya Al-Hoceima Massif, also found high mineralization of water, mainly characterized by a chloride-sodium or sodium-sulfate facies, resulting from marine intrusion and dissolution of evaporitic minerals in local rocks [5]. Furthermore, a multidisciplinary approach was used in a study on the coastal aquifer of Ghiss-Nekor to conduct a comprehensive hydrogeochemical and statistical analysis, evaluating groundwater quality and identifying the origin of salinity in this aquifer. The results revealed high salinity concentrations and dominant chemical facies comprising sodium, chlorides, and sulfates, primarily attributable to marine intrusion caused by normal faults along the plain, to the west and east, through which marine waters infiltrate[6]. The objective of this study was to carefully examine the physical characteristics of groundwater intended for human consumption during drought periods, as well as to evaluate the impact of marine intrusion in the region's groundwater. This study will contribute to developing a conceptual model of the aquifer system to monitor water quality, assess the nature and extent of marine intrusion, and identify sources of saline water. Thus, it will help in making appropriate management measures to avoid overexploitation and ensure the sustainability of groundwater reserves, as well as to address marine intrusion issues[7,8].

2 Presentation of the study area

The geographical context of the Al Hoceima region, located in northern Morocco, is characterized by its coastal position along the Mediterranean Sea. Bordered by the Rif Mountains to the east, offering a mountainous landscape and rugged topography, the region also features coastal plains and river valleys, providing a diversity of landscapes [9]. It enjoys a Mediterranean climate, with hot, dry summers and mild, humid winters. Even with variable precipitation, the Ghiss-Nekkor aquifer experiences water deficit due to high potential evapotranspiration, even with slight excess[10,11].

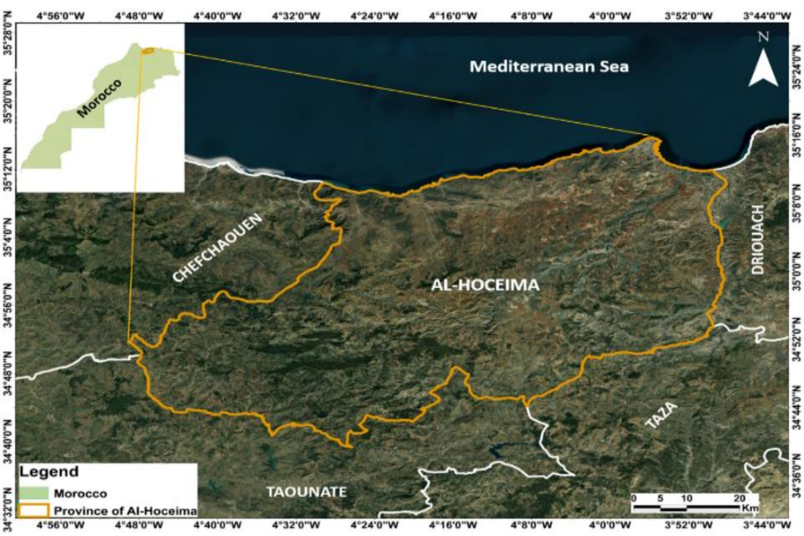


Fig.1: Geographic location of Al Hoceima region.

3 Materials and Methods

Throughout this study, a set of groundwater samples was methodically gathered from seven drillings according to an annual sampling plan, located approximately 3 km from the coastal region of Al Hoceima. The sampling sites were selected by the National Office of Water and Electricity - Water Branch after a geophysical and hydrological study to access the location of the boreholes. After several pumping tests, they are currently in operation to supply water to consumers' needs. Each sample underwent meticulous labeling and storage procedures following established protocols to ensure its integrity during transportation and analysis. The map below illustrates the positioning of the sampling points **Table1**, **Fig.2**. On-site evaluations using portable devices encompassed parameters such as temperature, pH, turbidity, electrical conductivity, and dissolved oxygen. Meanwhile, laboratory analysis employing volumetric methods scrutinized total hardness (TH), chlorides (Cl^-), and alkalinity. Additionally, sulfates (SO_4^{2-}), nitrites, boron, and silicate were quantified utilizing colorimetry with a spectrophotometer (7600 UV-VIS) **[12]**. Parameters like iron and ammonium were analyzed using kits (MQuant HC166320-Merck). The physicochemical results were then analyzed using principal component analysis (PCA) with SPSS software to identify correlations among the studied parameters. To identify correlations among the studied parameters and deepen the understanding of the structure of the hydrochemical data collected in this study, details have been provided on the variables chosen for analysis. These variables include the main relevant cations and anions for characterizing the chemical composition of groundwater**[13]**. The selection of these variables was based on their importance in the chemical composition of groundwater and their ability to explain observed variations. Cations such as sodium, potassium, calcium, and magnesium, as well as anions such as chlorides, sulfates, nitrates, and bicarbonates, were included due to their significant impact on the chemical composition of groundwater and their importance in characterizing hydrochemical processes. **[14]**.

Table 1. Sampling collection information.

Sampling date	Points	Nature	Operating flow l/s	Drawdown
10/01/2024	P1	Well	50	3,83
05/02/2024	F1	Drilling	40	10
	F2	Drilling	25	18,75
07/02/2024	F3	Drilling	40	3,57
07/03/2024	F4	Drilling	25	13,39
	F4	Drilling	20	15,98
12/03/2024	F5	Drilling	40	2,96

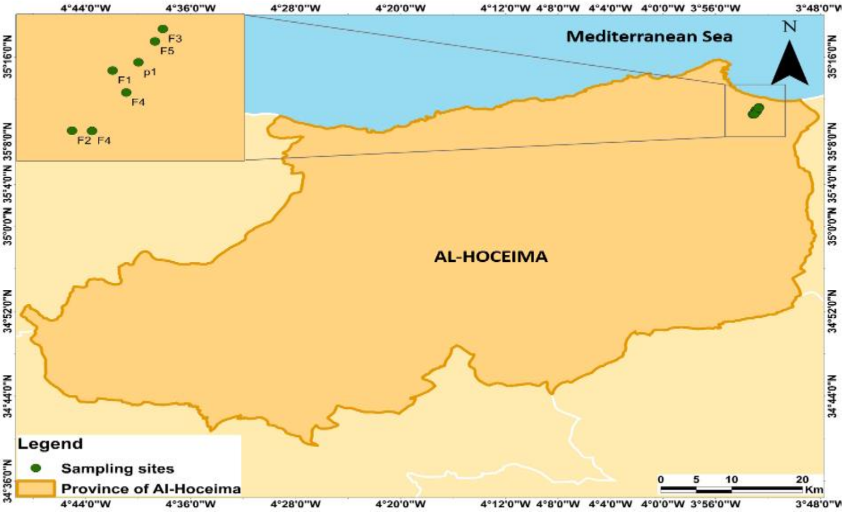


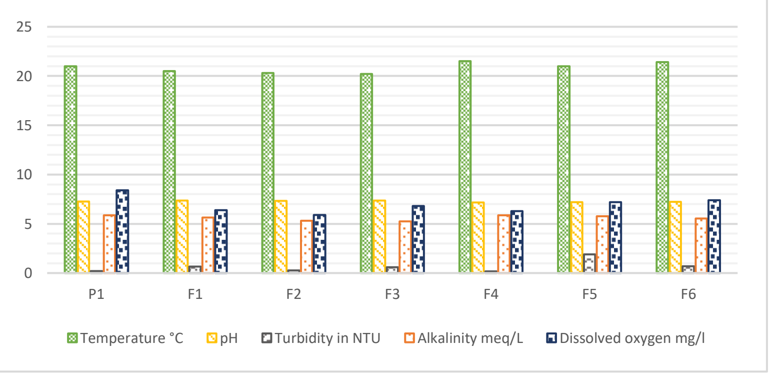
Fig.2: Location of Groundwater Sampling for Human Consumption in the Alhoceima Region.

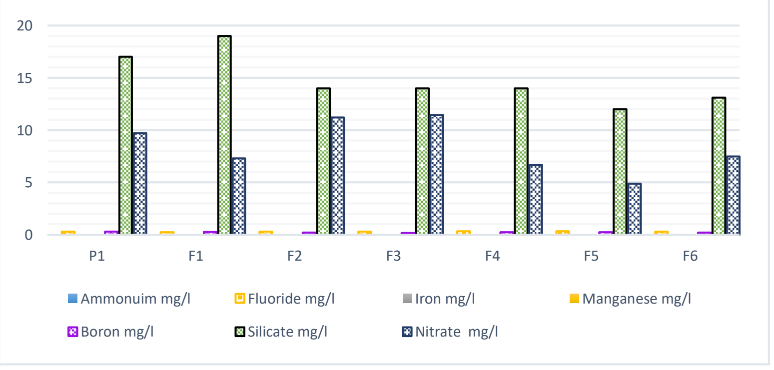
4 Results and discussion

The physico-chemical analysis of the seven groundwater samples, conducted at the laboratory of the National Office of Water and Electricity - Water Branch, as illustrated in Fig. 3, revealed temperature and turbidity levels within acceptable norms for these water samples, ranging between 0.2 and 1.9 NTU. The pH falls within the Moroccan standard range of 6.5 to 8.5 meq/L, with measured values ranging from 7.17 to 7.36 [5], indicating temperatures of 20.2°C to 21.4°C. This suggests that the sampled waters mainly originate from shallow aquifers. Alkalinity ranges between 5.3 and 5.85. Electrical conductivity, which is a reliable indicator of overall water mineralization, varies from 2580 to 2810 µS/cm. These values indicate significant variations in water chemistry; the lowest EC value corresponds to borehole F2, while the highest is recorded in borehole F5. According to WHO standards (2011), groundwater EC should not exceed 2700 µS/cm [15]. Sulfate concentrations range from 518 to 689 mg/L, and chloride concentrations from 415 to 628 mg/L, indicating that all points are below normative thresholds. As for hardness, calcium and magnesium vary respectively from 18.2 to 21 mg/L, from 10 to 12.25 mg/L, and from 6.75 to 9.7 mg/L. These values hold significant meaning for the different samples, highlighting the correlation between conductivity and mineral salt concentration [16]. Elements such as boron, manganese, silicate, fluoride, and iron showed low concentrations in all samples. However, nitrate and ammonium concentrations do not exceed standards, suggesting the absence of water pollution from intensive agriculture, organic matter decomposition, or contamination by wastewater or fertilizers [3,12].

To determine the most significant factors influencing groundwater chemistry, a principal component analysis (PCA) was conducted (Fig. 4). The hydrochemical variables were considered: electrical conductivity EC, magnesium ions Mg^{2+}, calcium ions Ca^{2+}, TH, SO^{4-}, F^-, chloride ions Cl^-, HCO_3, and NO_3^-. Two factors (F1 and F2) were utilized to strengthen observed trends and classify variables into four distinct groups. The first group includes alkalinity, EC, Cl^-, NH^{4+}, and total hardness TH, while the second group consists of Ca^{2+}, Mg^{2+}, SO_4^{2-}, and NO_3^-. HCO_3 alone forms the third group. The horizontal axis represents PC1, and the vertical axis represents PC2 [18]. The first principal component (PC1), explaining 34.3% of the variance, is strongly correlated with parameters such as EC, Ca^{2+},

Mg^{2+}, Cl^-, TH, and alkalinity. These associations suggest that these factors are closely related and have a significant influence on the chemical composition of the studied groundwater. The second principal component (PC2), which accounts for 27.85% of the variance, is primarily associated with the presence of sulfate ions (SO_4^{2-}) and nitrate ions (NO_3^-). This could indicate processes such as gypsum dissolution and contamination by nitrates from agricultural or anthropogenic sources[15]. These findings suggest that various geochemical processes and pollution sources contribute to the variability of groundwater chemical composition in the studied aquifer [19].
The results of this analysis provide crucial information for assessing groundwater quality and adjusting management practices. They identify potential sources of pollution, highlight the relationship between water mineralization and conductivity, and indicate the need to monitor contamination sources [4]. These findings can guide stricter regulations and sustainable agricultural practices to ensure safe and sustainable water supply.
Research in the same region has revealed an increase in chloride and sulfate levels. Samples from the Ghiss-Nekkor plain show that high chloride concentrations in wells near the coast suggest seawater intrusion, while untreated polluted discharges account for elevated chloride levels in areas distant from the marine intrusion threat [20]. Most samples from the Bou-Arega aquifer show signs of chloride enrichment, with lower Na/Cl ratios and higher Cl/Br ratios than seawater [19]. Some samples exhibit sodium excess, suggesting potential saltwater intrusion. Groundwater in the Gareb plain is highly saline, demonstrating elevated concentrations of chloride, sulfate, sodium, magnesium, and calcium[21]. While generally showing chloride enrichment, the absence of clear geochemical evidence suggests this excess is likely due to pollution. High salinity primarily results from water-rock interaction processes such as carbonate dissolution and cation exchange with silicates [22].





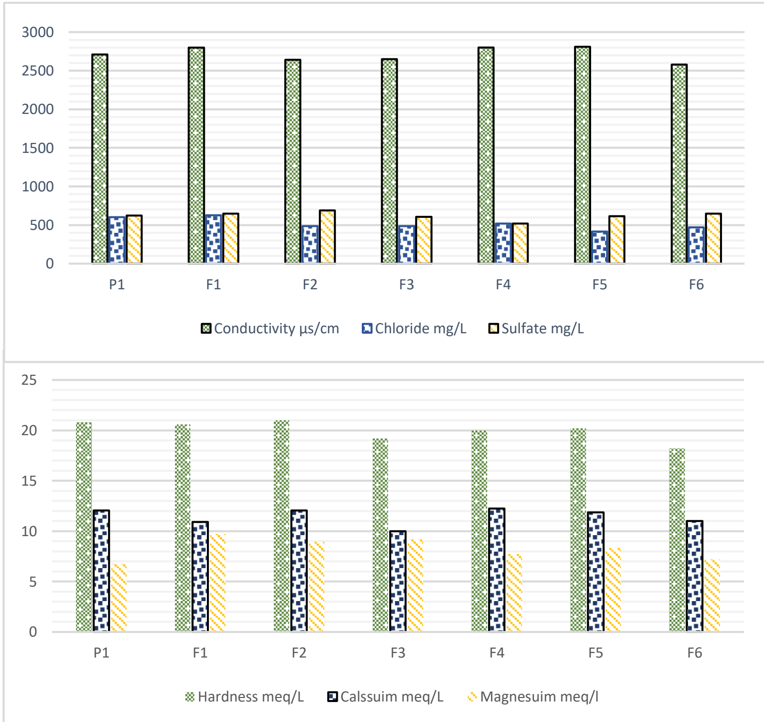
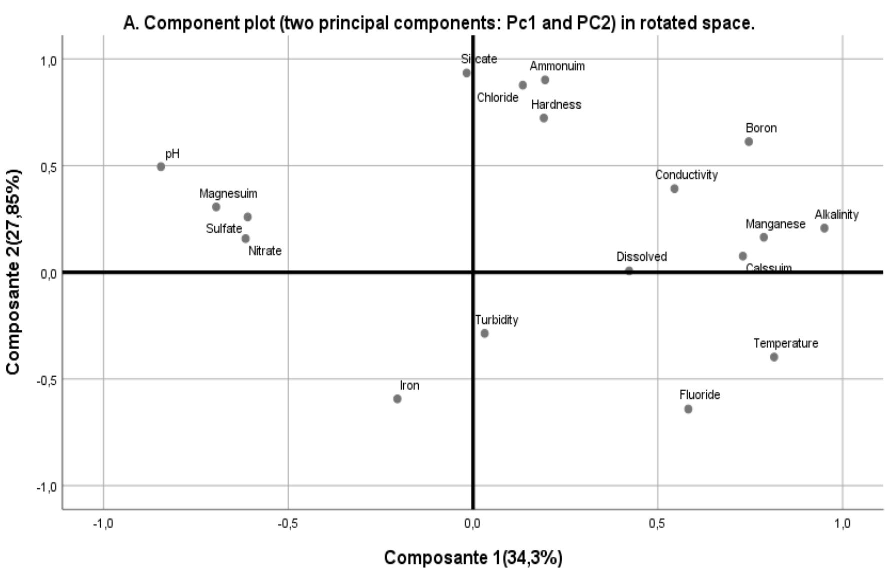


Fig.3. Results of the physicochemical analysis of groundwater in the Al Hoceima region.



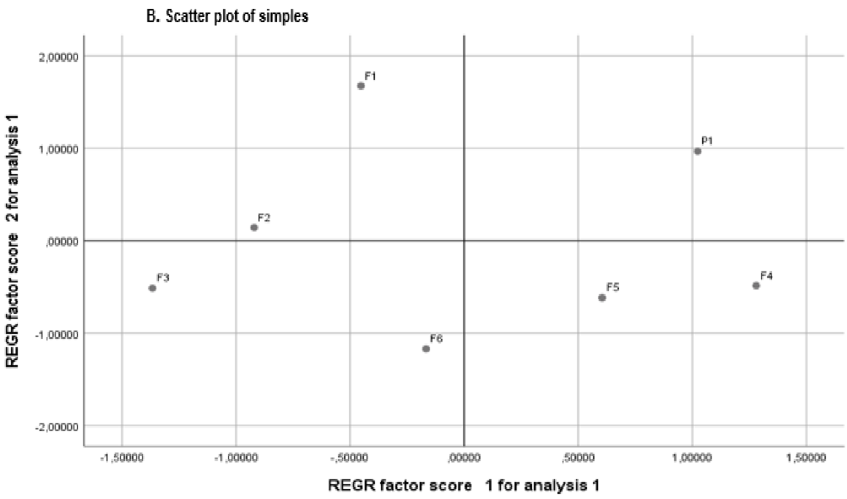


Fig.4. Principal Component Analysis (PCA) for groundwater samples.

5 Conclusion

The results of this physico-chemical analysis highlight the quality and composition of groundwater in the Al Hoceima region. With temperature, turbidity, and pH levels within standards, and concentrations of ions and mineral elements varying within acceptable ranges, these data suggest a primarily shallow aquifer origin. Additionally, principal component analysis (PCA) reveals significant associations between certain parameters, notably electrical conductivity, calcium, magnesium, chloride ions, and total hardness, influencing the groundwater's chemical composition. The concentrations of sulfate and nitrate, linked to the second principal component, raise concerns about potential contamination, likely stemming from agricultural or anthropogenic activities. The conclusions of this study have significant implications for policymakers and provide crucial guidance for future research in the Al Hoceima region. To ensure groundwater sustainability, policymakers are encouraged to strengthen regulations regarding potential sources of contamination, enhance monitoring systems, and integrate conductivity measurements into groundwater monitoring programs. Future research initiatives should prioritize investigating specific sources and mechanisms of contamination, assessing the impact of anthropogenic activities, and developing predictive models to anticipate changes in groundwater quality and availability. Ultimately, proactive measures and targeted research efforts are essential to safeguard groundwater resources and ensure their long-term sustainability in the Al Hoceima region.

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