Exploring salinity origins in the Ghiss-Nekor aquifer, northern Morocco: a multivariate statistical analysis

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Abstract. The Ghiss-Nekor coastal aquifer is characterized by high salinity stemming from multiple sources, remains poorly investigated. This study aims to address this knowledge gap by employing both univariate (descriptive statistics) and multivariate statistical analyses, including correlation matrix and principal component analysis (PCA). Groundwater samples were collected from 52 sites across the study area and meticulously analyzed for pH, TDS, EC, and the ions such as Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+, HCO_3^-, NO_3^-, NO_2^-,Cl^-, SO_4^{2-}, PO_4^{3-}, and SiO_2. Descriptive statistics, notably standard deviation (SD), highlight the diverse sources contributing to salinization, among which seawater intrusion (SWI) emerges as a significant factor. Correlation matrix analysis underscores multiple pathways for salinization, implicating SWI, salt dissolution, chemical weathering, secondary salt leaching, and anthropogenic activities. PCA elucidates 81.05% of the total variance in physicochemical parameters, with strong loadings observed for EC, Na^+, Cl^-, and Mg^{2+}, corroborating the influence of SWI and suggesting evaporation processes. Moreover, PCA reinforces the potential influence of both geogenic and anthropogenic factors in salinization within the study area. This comprehensive investigation provides valuable insights into the elevated salinity levels observed in the Ghiss-Nekor aquifer, contributing to a deeper understanding of its hydrogeochemical dynamics.

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1 Introduction

Groundwater salinization has emerged as a global environmental concern, exerting significant impacts on countries worldwide. It incurs substantial ecological and economic costs while posing a threat to global health [1], and is widely recognized as a major form of water pollution [2]. Managing and governing groundwater effectively proves challenging, particularly in arid and semi-arid environments [3, 4]. Therefore, it is crucial to identify the sources of groundwater salinization and comprehend the underlying processes and mechanisms, especially in coastal aquifers due to their complex nature and diverse sources.

One of the effective multivariate statistical methods is the Principal Component Analysis (PCA), which plays a pivotal role in identifying sources of salinity in aquifers. By condensing numerous physicochemical parameters of groundwater into key factors, this method facilitates understanding of the aquifer characteristics and behavior regarding salinization and other water pollution sources [5, 6].

The Ghiss-Nekor aquifer serves as the primary groundwater storage in the Al-Hoceima province, a semi-arid Mediterranean area plagued by elevated groundwater salinity. This issue complicates drinking water supply management, worsened by reduced regulation capacity of the prinipal dam in the area (MBAK dam) as a result of silt accumulation [7]. Understanding the origins of salinization in this area is pivotal for managing the region's drinking water resources effectively.

Several studies have assessed the physico-chemical quality of groundwater in the Ghiss-Nekor plain, including those by [8], [9], [10], [11], [12], [13], [14], [15], and [16]. This study aims to complement these efforts by employing both univariate and multivariate statistical analyses to discern potential sources of salinization in the Ghiss-Nekor aquifer, by using the descriptive statistics, correlation matrix, and principal component analysis (PCA). This approach, emerging as an indispensable tool for informing water management strategies, aims to unravel the intricacies of groundwater salinity origins.

2 Study area

The Ghiss-Nekor plain (Fig. 1) lies southeastern Al-Hoceima in Northern Morocco. The area is intersected by the Ghiss River, which flows through the northwest, and the Nekor River, which traverses its center. Beneath the plain lies the Ghiss-Nekor aquifer, regarded as a principal alluvial aquifer in Morocco's Mediterranean region, spanning approximately 90 km^2. Estimates suggest the aquifer holds total reserves of around 328 million cubic meters (MCM) [17]. Geographically, the plain is delimited by the Imzouren-fault (NNW-SSE) to the West and the Trougout-fault (N-S) to the East; these faults are characterized as normal faults with a strike-slip component [18]. Geological formations within the aquifer (Fig. 2) extend from depths of 200 to 450 meters and mainly comprise coarse sand and gravel, with occasional mixtures of clay and silt, along with sporadic clay-marly lenses. Additionally, there is a wide clayey layer that extends prominently along the coast. Beneath the aquifer lies a bedrock composed of impermeable shale substratum. The region experiences a semi-arid Mediterranean climate, marked by gentle, rainy winters and scorching, arid summers. Rainfall typically occurs from October to April, while the dry, hot season extends from May to September. On average, the study area experiences a yearly temperature of 18°C, with intermittent yearly rainfall averaging 346mm [19].

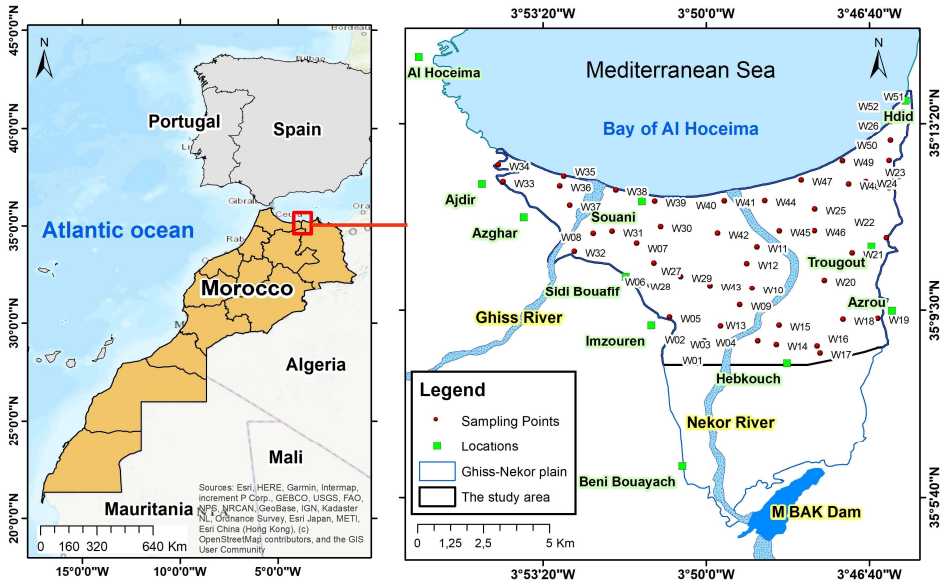

Fig. 1. The study area location.

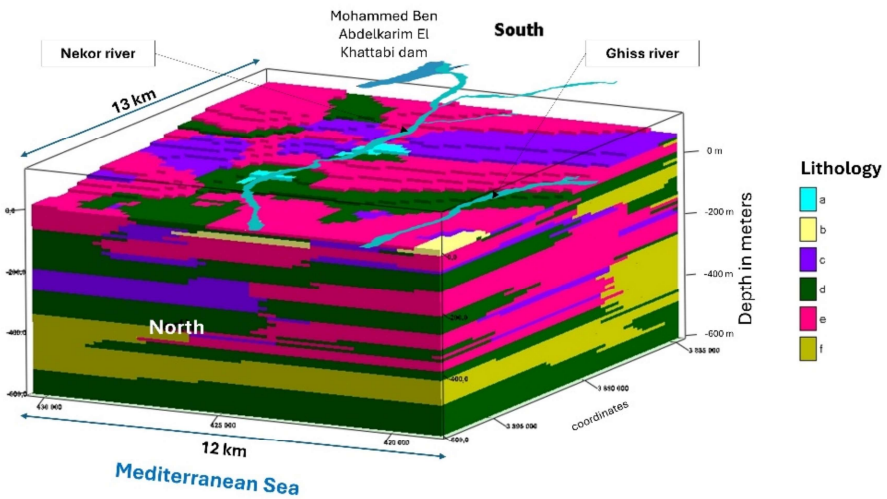

Fig. 2. Lithologic model of the Ghiss-Nekor aquifer. Lithology: (a) Abundance of gravel and pebble, (b) Abundance of shell sand, (c) Alluial deposit with silt and clay, (d) Clay, marl, and silt, (e) Coarse sand and gravel, (f) Shale.

3 Materials and methods

In January 2022, groundwater sampling was conducted in accordance with the guidelines set forth in the 9th edition of "Water analysis" [20], including storage, transportation, and laboratory analysis procedures. The parameters T (temperature), pH (acidity or alkalinity), and EC (electrical conductivity) were measured using the Multifunction pH Meter PCE-PHD-1. Total dissolved solids (TDS) were determined by summing the levels of cations and

anions present in the water samples. Sodium (Na^+) and potassium (K^+) levels were determined using ELICO Digital Flame Photometer CL- 378 with an accuracy of ± 0.5 ppm. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were analyzed via titration with EDTA. Chloride ions (Cl^-) were measured through titration with silver nitrate (0.1 N), while bicarbonate ions (HCO_3^-) were determined using titration with hydrochloric acid (0.1 N). Nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), and silica (SiO_2) levels were quantified using a colorimetric determination method with a Hach Lange DR 6000 UV-VIS Spectrophotometer, with a precision of ± 1 nm.
The univariate and the multivariate statistics were conducted using SPSS 25.0 software. These methods are commonly used and beneficial for examining large datasets to comprehend geochemical assessments and pinpoint potential geological factors affecting groundwater chemistry.

4 Results and discussion

4.1 Descriptive statistics

Table 1 presents a summary of the essential data regarding the physicochemical properties of the Ghiss-Nekor groundwater. The pH levels range from 7.1 to 8.2, indicating an alkaline nature, with an average of 7.6. It is notable that the pH exhibits a very low standard deviation (0.3), suggesting a consistent source across samples [21]. The EC ranges from 1612 to 15300 µS/cm, averaging 4076.3 µS/cm, while the TDS vary from 1449.5 to 10014.8 mg/L, with an average of 3043.6 mg/L. Cation abundance follows the sequence: $Na^+ > Ca^{2+} > Mg^{2+} > K^+ > NH_4^+$, whereas anions follow: $SO_4^{2-} > Cl^- > HCO_3^- > NO_3^- > PO_4^{3-} > NO_2^-$. This order of abundance aligns with findings by [22] upstream of the Ghiss-Nekor plain.

The variability in measured concentrations of hydrochemical parameters, as indicated by their standard deviations, is substantial, with notable observed disparities, particularly in Cl^- (823.6 mg/L), which ranges from 156 to 5140.7 mg/L, and averages 858.6 mg/L. These fluctuations imply the presence of multiple potential sources of salinization within the study area [23]. Seawater intrusion is identified as a potential contributor to salinization, evident from significant fluctuations (SD) in EC (2337.8 µs/cm) and TDS (1520.2 mg/L) [21].

Table 1. Descriptive statistics of the measured groundwater parameters.

Parameter		Mean	Median	Minimum	Maximum	Std. deviation
pH	-	7.6	7.6	7.1	8.2	0.3
EC	(µs/cm)	4076.3	3480.0	1612.0	15300.0	2337.8
TDS		3043.6	2717.5	1449.5	10014.8	1520.2
Na^+		529.6	436.0	137.0	2560.0	413.8
K^+		7.2	4.3	1.7	40.4	7.7
Mg^{2+}		142.7	131.0	56.6	395.5	65.6
Ca^{2+}		226.9	223.6	59.3	415.2	74.5
NH_4^+		0.0187	0.0141	0.000	0.182	0.0294
Cl^-	mg/L	858.6	627.5	156.0	5140.7	823.6
SO_4^{2-}		873.1	857.4	235.1	1592.2	312.6
HCO_3^-		377.8	359.9	152.5	713.7	104.1
NO_3^-		29.526	19.790	<DL*	123.360	26.681
NO_2^-		26.379	0.000	<DL*	1371.0	190.122
PO_4^{3-}		0.0795	0.0422	<DL*	0.5413	0.1109
SiO_2		20.5	15.3	5.5	81.0	16.6

* DL : Detection limit. The DL for NO_3^-, NO_2^-, and NH_4^- are 0.01 mg/L, 0.03 mg/L, and 0.002 mg/L, respectively.

4.2 Correlation analysis of hydrochemical parameters

The correlation matrix was employed to evaluate the extent of association among different groundwater parameters, as outlined in Table 2. A robust association between these parameters is indicated by coefficients of +1 or -1, while 0 signifies no connection. Values falling between +0.50 to +0.70 suggest moderate correlation, those between +0.70 and +0.90 indicate high correlation, and coefficients at +0.90 or above signify very high correlation. These three correlation coefficient categories were highlighted in bold within the correlation matrix. The significant positive associations of (Na^+, Cl^-, Mg^{2+}, and K^+) with (EC and TDS) underscore that these major ions predominantly govern the observed high salinity, likely originating from common sources [21], such as seawater intrusion occurrence [24] and salt dissolution [4, 25]. The exceptionally strong correlation between Na^+ and Cl^- (+0.99) underscores the influences of chemical weathering, secondary salt leaching, and seawater intrusion [26–28]. Likewise, the strong correlation between Ca^{2+} and SO_4^{2-} (+0.92) indicates a possible shared origin, such as gypsum ($CaSO_4.\ 2H_2O$) or anhydrite ($CaSO_4$) dissolution [4, 28, 29]. However, the substantial correlations of Mg^{2+} with Ca^{2+} (+0.74), Na^+ (+0.84), and Cl^- (+0.85) highly suggest common origins, chiefly seawater intrusion and carbonate dissolution [28]. The significant correlations between K^+ and Na^+, as well as Cl^-, imply a shared source, particularly near the shoreline where these ions are abundant, suggesting that seawater infiltration could be a potential factor contributing to salinity increase in coastal areas [25]. SiO_2 demonstrates a high correlation with PO_4^{3-} (+0.95) and moderate correlations with NO_3^- (+0.60), with SiO_2 being geogenic while PO_4^{3-} and NO_3^- are predominantly anthropogenic, originating from sources like septic systems, manure, and commercial fertilizers [30]. The strong correlation between SiO_2, PO_4^{3-}, and NO_3^- can be attributed to enhanced silicate weathering due to the nitrification process [31]. Weak to very weak correlations between NH_4^+, NO_3^-, NO_2^-, PO_4^{3-} with most variables (EC, TDS, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-) indicate diverse sources for these ions, suggesting human activities such as sewage leaks and agricultural practices have influenced groundwater chemistry. The presence of a highly insignificant negative correlation ($-0.37 < r < 0.32$) observed between pH and the other parameters suggests minimal impact of pH fluctuations on groundwater salinity [25].

Table 2. Matrix of correlations of the measured parameters.

Ions	Na^+	K^+	Mg^{2+}	Ca^{2+}	NH_4^+	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-	NO_2^-	PO_4^{3-}	SiO_2	EC	TDS	pH
Na^+	1														
K^+	**.79**	1													
Mg^{2+}	**.84**	**.56**	1												
Ca^{2+}	.49	.20	**.74**	1											
NH_4^+	.14	.24	.23	.18	1										
Cl^-	**.99**	**.77**	**.85**	**.50**	.16	1									
SO_4^{2-}	.38	.14	**.69**	**.92**	.20	.36	1								
HCO_3^-	.19	.02	.26	-.01	-.09	.14	.02	1							
NO_3^-	.21	.18	.04	-.15	.03	.19	-.16	.12	1						
NO_2^-	.26	.17	.11	-.14	-.05	.24	-.12	.19	.33	1					
PO_4^{3-}	.18	.25	-.06	-.29	-.03	.16	-.36	.16	**.61**	.03	1				
SiO_2	.18	.22	-.08	-.26	-.04	.16	-.37	.14	**.60**	.05	**.95**	1			
EC	**.99**	**.75**	**.91**	**.60**	.18	**.99**	.49	.19	.19	.15	.12	.12	1		
TDS	**.97**	**.71**	**.93**	**.68**	.18	**.96**	**.58**	.21	.15	.15	.07	.07	**.99**	1	
pH	-.22	-.04	-.18	-.26	.32	-.19	-.18	-.37	-.03	.05	-.18	-.23	-.22	-.25	1

4.3 Principal component analysis (PCA)

PCA analysis was employed to explore the underlying sources of variation in hydrochemical variables, condensing a multitude of individual parameters into a more concise set while preserving their inherent attributes [23]. This approach aids in spotlighting the primary

variables impacting groundwater chemistry. In this study, PCA was executed through orthogonal varimax rotation alongside Kaiser normalization, a frequently employed rotation method known to mitigate the influence of less significant groundwater quality parameters identified through PCA analysis [32]. The analysis focused on 13 chosen variables representing the geochemical framework. To assess the dataset's suitability for PCA, Kaiser Meyer Olkin (KMO) and Bartlett's tests [33] were conducted, with the results detailed in Table 3. A KMO value exceeding 0.5 and a Bartlett's test significance below 0.05 reflecing significant correlation within the data. In this investigation, the KMO sufficiency value stood at 0.642, with a significance value of less than 0.001.

Four principal components (Eigenvalues >1) were selected, collectively explaining 81.05% of the total variance. Component 1 accounted for 40.12%, component 2 for 23.21%, component 3 for 9.60%, and component 4 for 8.12%. Table 4 presents the respective loadings for each component, with loadings exceeding 0.65 highlighted. These were employed to examine the connections between components and hydrochemical parameters [23].

Component 1, termed the "salinization component," displays strong positive loadings for EC, Na^+, Cl^-, Mg^{2+} with values of +0.98, +0.94, +0.96, and +0.92, respectively, and moderately positive loadings for K^+, Ca^{2+}, and SO_4^{2-} with values of +0.78, +0.63, and +0.54, respectively, suggesting potential influence from seawater intrusion. Component 2 showcases robust positive-loadings for PO_4^{3-} (+0.91), SiO_2 (+0.90), and NO_3^- (+0.67), indicative of anthropogenic sources such as domestic sewage and agricultural run-off [31]. Component 3 is characterized by a strong positive loading of NO_2^-, pointing to pollution from human activities, particularly evident in urban areas such as Imzouren [9, 33]. Component 4 displays a moderately positive loading of NH_4^+, likely attributed to agricultural practices or sewage seepage [35], while HCO_3^- exhibits a negative correlation, indicative of natural processes like carbonate mineral dissolution [36].

These PCA findings highlight complex hydrogeochemical processes, including weathering of recharge area material, evaporation, seawater intrusion, and anthropogenic influences such as agriculture and residential sewage seepage.

Table 3. Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity.

Tests		**Measured value**
Kaiser-Meyer-Olkin (KMO) Measure of sampling sufficiency		.64
Bartlett's test of sphericity	Approximate Chi-Square value	987.71
	df	78
	Sig.	<0.001

df: degrees of freedom; Sig. : significance

Table 4. Rotated matrix of components for the measured parameters.

Parameters	Component			
	1	**2**	**3**	**4**
EC	**.98**	.02	.09	-.02
Na^+	**.97**	.12	.04	-.04
Cl^-	**.96**	.10	.04	.00
Mg^{2+}	**.92**	-.24	.13	-.06
K^+	**.78**	.29	-.15	.19
Ca^{2+}	.63	-.56	.28	.10
PO_4^{3-}	.13	**.91**	.07	-.05
SiO_2	.12	**.90**	.10	-.05
NO_3^-	.13	**.67**	.57	.03
SO_4^{2-}	.54	-.64	.26	.10
NO_2^-	.05	.05	**.87**	-.08
HCO_3^-	.22	.10	-.03	-.78
NH_4^+	.25	-.02	-.10	**.68**
Eigenvalue	5.22	3.02	1.25	1.06
Variance (%)	40.12	23.21	9.60	8.12
Cumulative (%)	40.12	63.33	72.93	81.05

The highlighted values indicate positive-loadings of the associated parameters within the extracted components.

5 Conclusion

The study provides a comprehensive understanding of the elevated salinity levels observed in the Ghiss-Nekor aquifer, shedding light on the hydrogeochemical dynamics and underlying sources of salinization in the region. Through a combination of descriptive statistics, correlation matrix analysis, and principal component analysis (PCA), the study elucidates the complex interplay of various factors contributing to groundwater salinity. The findings reveal significant correlations among physicochemical parameters, emphasizing the dominant influence of seawater intrusion, salt dissolution, chemical weathering, secondary salt leaching, and anthropogenic activities. PCA analysis further consolidates these insights, identifying distinct components associated with salinization, anthropogenic contamination, and specific pollutants originating from human activities such as agriculture and urban sewage. Moreover, the study highlights the multifaceted nature of hydrogeochemical processes within the Ghiss-Nekor aquifer, including weathering of recharge area materials, evaporation, and the intricate interplay between geogenic and anthropogenic influences. These insights are crucial for formulating effective water management strategies aimed at mitigating salinity issues and preserving the quality of groundwater resources in the region.

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