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Research Article

The use of multivariate statistics and hydrogeochemical analyses for the characterization of groundwater mineralization. A case study of El Hadaiek aquifer, Nord-East of Algeria

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Abstract:

A comprehensive understanding of the physicochemical characteristics of water is essential for evaluating its availability and significance. The study area, located in northeastern Algeria, is characterized by intensive groundwater exploitation, particularly for agricultural activities. Therefore, assessing the quality and characteristics of this resource is crucial. This study aims to evaluate groundwater quality in the El Hadaiek aquifer using multivariate statistical methods and hydrogeochemical analyses, with a focus on identifying the contribution of major ions to groundwater mineralization.A systematic investigation of physicochemical parameters was conducted on collected water samples. The results were analyzed using hydrochemical methods, including the Piper diagram, to identify water facies, alongside multivariate statistical techniques. Principal Component Analysis (PCA), combined with varimax rotation, was applied to determine the main processes controlling water mineralization and to identify relationships among water samples. Additionally, the Saturation Index (SI) was calculated to identify the key geochemical reactions governing the system.The results indicate that groundwater in the study area is slightly acidic and highly mineralized. Most measured parameters remain within the limits established by the World Health Organization (WHO). The dominant hydrochemical facies is characterized by sulfate and chloride with calcium and magnesium (Ca–Mg–SO_4–Cl type). Two principal processes control groundwater mineralization: recharge through soil infiltration and water–rock interaction (the primary mechanism for major ion generation), with a lesser contribution from anthropogenic activities.

1. Introduction

Contamination of the water supply poses a health hazard and raises the price of water treatment. In 2012, 43% of the 842,000 deaths from diarrhea were children under five years old. 502,000 of these deaths were caused by poor drinking water (Jamison et al, 2017 and Djimi et al, 2021)**.** The United Nations believes that universal access to safe drinking water helps reduce poverty (WWAP, 2021). In the literature, the relationship between hydrogeology and water quality is not well understood. The demand for freshwater, such as groundwater, has increased slightly in many parts of the world due to population explosion, urbanization, and domestic activities. This led to an apparent increase in the concentration of certain constituents, such as Total Dissolved Solids (TDS), nitrate, chloride, and sulphate, in groundwater (Ledesma-Ruiz et al., 2015 and Nyam et al, 2020). Furthermore, climate change is expected to increase stress on the hydrologic system (Nyam et al, 2020).El Hadaiek aquifer is located in Northeast of Algeria. Numerous geophysical, geological and hydrogeological studies have been conducted to better understand the subsoil. This resulted in the understanding of tectonic accidents, the existence of underground layers, and the identification of aquifers. From these studies, it is possible to assesses groundwater reserves and determine their characteristics. Understanding the quality of groundwater is crucial for safeguarding public health and promoting sustainable use of water resources. Although the latter would contribute to a better understanding and evaluation of the quality of these waters, the origin of the mineralization of these waters was not established . It is urgently necessary to adopt a precautionary approach in order to improve drinking water quality (Folifac et al, 2009). It is also essential to identify water pollution sources, whether they are natural or anthropogenic, as these can have a significant influence on water parameters (Nguyen et al, 2020). Hydrochemical and multivariate statistical methods are two research approaches that provide helpful information for implementing such solutions. Multivariate statistical methods mainly include principal component analysis (PCA). The PCA method is a dimension-reduction technique that, by focusing on the most important aspects, offers both quantitative and qualitative information about possible sources of pollution and a more straightforward representation of the data (Tomaz et al, 2020). Many researchers have employed this technique (BenAmmar et al., 2014; Bouteldjaoui et al., 2016; Kabour and Chebbah, 2017; Gouaidia et al., 2018; Amrani and Hinaje, 2014; Melouah and Zerrouki, 2020; Fenazi et al 2022). Hydrochemistry facilitates the simultaneous assessment of the hydrogeochemical processes responsible for the temporal and spatial variations in groundwater chemistry (Zekâi ¸Sen, 2015; Reyes-toscano et al, 2020). Research has demonstrated that the evaluation of surface water quality requires consideration of physicochemical characteristics, such as temperature, pH, and turbidity, but the evaluation of groundwater quality requires consideration of hydrochemical parameters, such as major cations and anions (Vadiati et al, 2016). Therefore, the current study focused on groundwater resources of the El Hadaiek aquifer. The purpose of this study is to identify the hydrogeochemical processes that control groundwater quality (mineralization) in the study area by the use of hydrogeochemical methods and multivariate statistical analysis techniques.

2. Description of the study area

The study area is part of the "Zeramna" valley. It is located in the North-East of Algeria, 7-km South-West of Skikda (Boucenna, 2007). The climate of the study area is a humid characterized by a cold and rainy winter and a hot and humid summer (Boubeli, 2018). El Hadaiek aquifer is part of the geological ensemble of the Little Kabyle mountain range. The study of Zeramna Wadi presents a varied geology, with a combination of recent and ancient sedimentary deposits. Part of this region is occupied by alluvial, sandstone and quaternary formations Pouding, Numidian gray, while the other part consists of impermeable clayey and metamorphic formations. The Zeramna wadi is one of the main tributaries of the Saf-Saf wadi (Figure.1) flows across the plain through orchards and the city of Skikda (Boubeli, 2018).

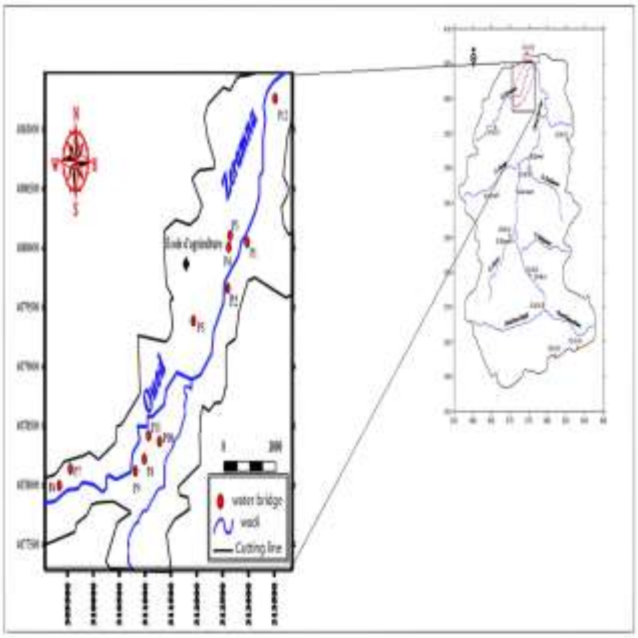

Figure 1. *Location of the study area.(Modified by the author after Debbech;B &Guemari.D 2017)*

The Figure 2 shows that the flow direction of the surface water table starts from the South-West to the North and the spacing between the iso-piezometric-lines is narrower in the South; the slope is higher than in the North.

2.1. Geology

In this section, we shall confine ourselves to describing the geological formations that outcrop within our study area. From a geological perspective, the Zeramna wadi sub-basin comprises several distinct units, all of which fall entirely within the Tellian Atlas (Figure. 3 and 4).

2.1.1. Sedimentary soils

- Current alluvial deposits: These consist of silty deposits from the floodplains of the Saf-Saf and Zeramna rivers and from the marshy plain formed by the confluence of these two wadis.

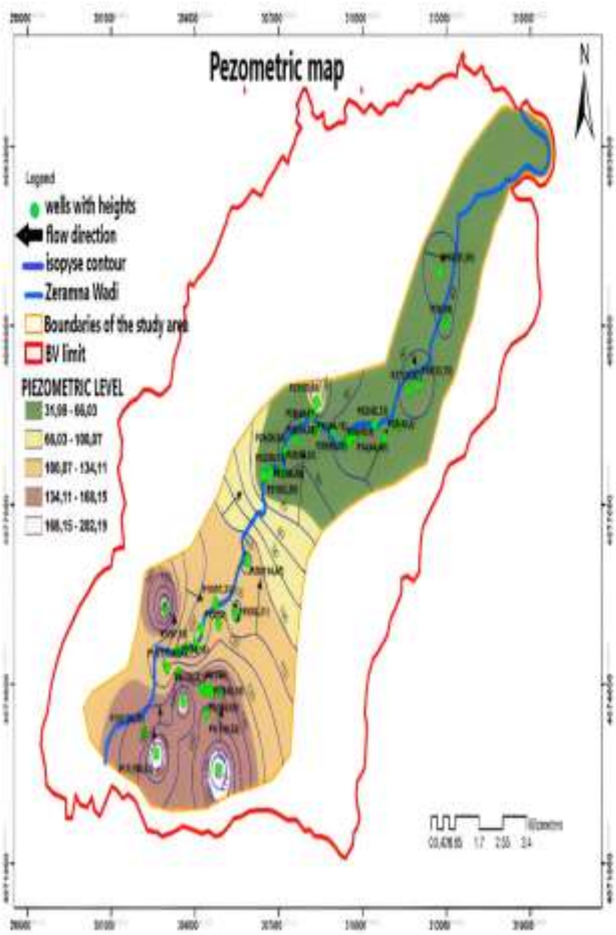

Figure 2. Piezometric map of the aquifer. (afterBoutldja .T & .Kafi.A.2023)

- Recent alluvial deposits: These consist of silt and rounded pebbles from the valley floors.
- Ancient alluvial deposits of the valleys (lower level) These are terraces of silt and rounded pebbles, 20 metres high or less; this is the current riverbed of the Saf-Saf and Zeramna.
- Numidian sandstone: These are fine-grained, yellowish sandstones, in which thin clay-sand layers are observed at various levels; they form the crown of some of the hillocks that dot the Tamalous cirque and occupy the entire southern half of Djebel Soubouyou.
- Clays and sandstones: (Lower Numidian) These are black clays containing thin beds of yellow sandstone, at the base of the preceding formation at the bottom of the Tamalous cirque and in Djebel Soubouyou.
- Puddingstones and Sandstone The constituent elements of the puddingstones are pebbles of gneiss, schist and, above all, clayey quartz, which are fairly irregularly distributed within the sandstone or clay layers; the thickness of the formation as a whole varies from 10 to 50 metres. They are well developed on the edge of the Tamalous cirque and in the Djebel de Soubouyou. These puddingstone formations are found at the base of the ancient massif in the lower valley of the Oued Bibi near El-Hadaiek, at the Skikda cemetery and at the Barrot farm; their extent clearly indicates that the subsoil of the Quaternary Sahal of Skikda is composed of clays, and the silts of this depression are so strongly clayey that they can be used as brick-making clay.

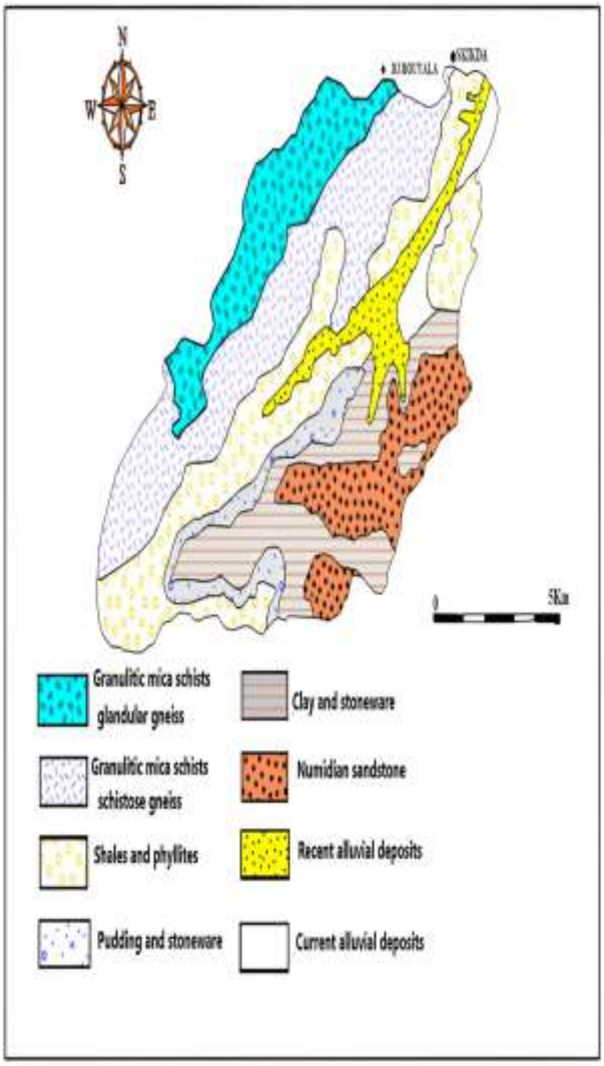

Figure 3. Geological map of the study area.(Modified by the author after.Khanouf & Hamadouch.)

2.1.2. Metamorphic terrain

- Schists and phyllites: These are bluish, clayey, talc-bearing, sericite-bearing or satin-textured sandstones, cut by numerous, often lenticular veins of milky quartz. These rocks form a large part of the Djebel Habia, Soubouyou, Skikda and Bon-yala ranges to the east and south of Skikda.
- Granulitic mica schists (schistose gneiss) Sometimes alternating with mica schists and forming the transitional zone between true gneiss and mica schists or micaceous schists.
- Granulitic mica schists (glandular gneiss) These constitute the main part of the Skikda massif and, in particular, the entire region of the ridges between the sea and the Guebli wadi.

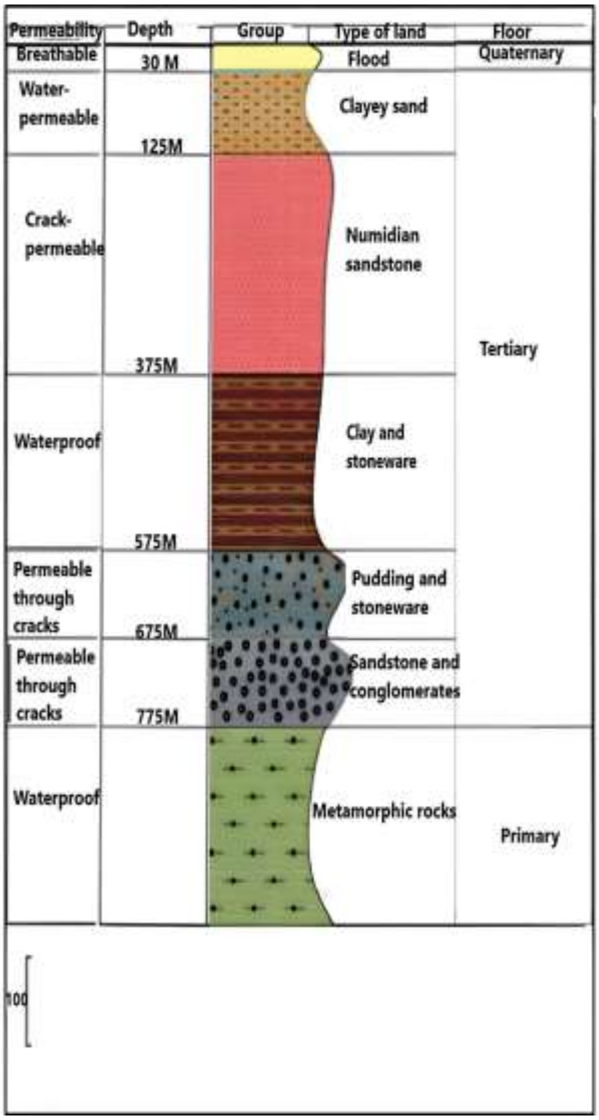

Figure 4. *A synthetic lithostratigraphic log of the study area (Modified by the author afterBoutldja .T & .Kafi.A.2023)*

3. Materials and Methods

This study was carried out in the area of El Hadaiek (Skikda). The measurement sites are diverse (urban and rural). Data collection took place from March 10 to April 03, 2024. Twelve (12) water points were sampled (Table 1). The water's physical parameters were measured using multi-parameter Type WTW multi 3420 equipment and a WTW cond 3110 device to measure conductivity in situ. The major ions were assessed using high-performance ion liquid chromatography (HPILC). We employed a Metrohm chromatograph equipped with CI SUPER-SEP columns for the analysis of anions, along with phthalic acid and acetonitrile as the eluent. The ion balance error was less than 5% for all samples.To classify waters and determine their origin, several scientists have employed statistical techniques like Principal Component Analysis (PCA) (Belkhiri et al., 2010; Varol et al., 2012; Salman et al., 2015; Boughariou et al., 2018; Bouteraa et al., 2019; Fenazi et al, 2022). PCA is widely utilized due to its straightforward algebra and direct interpretation (Farnham et al., 2003; Boughariou et al., 2018; Fenazi et al, 2022). In order to retain as much information as possible, it can be thought of as a projection method that projects observations from a p-dimensional space with p variables to a k-dimensional space (where $k < p$) (Fenazi et al, 2022). The total variance of the scatter plots with regard to the starting dimensions was used in this study to measure the information (Paul et al., 2013). The varimax rotation was conducted on the primary components to facilitate the interpretation of the factors in accordance with the natural or anthropogenic processes that regulate water mineralization. In this study, PCA was conducted on all 12 groundwater samples obtained from the site. Multivariate statistical methods were implemented using Statistica 13.4.0 software package.Twelve variables, namely physicochemical parameters (T°, pH, TDS and EC) and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-} and NO_3^{-}) were considered. The hydrochemical method required the use of the Piper diagram under the software diagrams for the hydrochemical classification of water (Eblin Sampah and Sombo Abé, 2014). The results of the physico-chemical analysis obtained have been analyzed using hydrochemical methods. This method needed the use of the Piper diagram (Piper, 1944) under the software diagrams for the hydrochemical classification of water (Eblin Sampah and Sombo Abé, 2014).

The equilibrium state of the water with respect to a mineral phase can be determined by calculating a Saturation Index (SI) using analytical data (Garrels and Mackenzie, 1967). To determine which geochemical reactions are crucial for regulating processes, Observing changes in saturation state in water chemistry is very important (Coetsiers and Walraevens, 2006; Aghazadeh et al., 2016).

$$IS = \text{Log}\,(IAP)/K \quad (1)$$

Where: **IAP** is the ion activity product of the dissociated chemical species in solution, and K represents the equilibrium solubility.

In natural and polluted waterways, PHREEQC is used to simulate chemical interactions and transfer. Saturation Index was calculated using this Software (PHREEQC) (Parkhurst and Appelo, 2013). The value of this index may be zero when the water is saturated by the mineral in question, positive when oversaturation, and negative when undersaturation with respect to this mineral.

4. Results and discussions

4.1. Assessment of groundwater physico-chemistry

The interpretation of physical and chemical characteristics for potable water use followed World Health Organization Standards (WHO, 2017). The results of physicochemical analysis are presented in Table 1. The pH values of the water samples range from 6.1–7 indicating that all water samples are alkaline. EC values ranged between 991–1685 uS/cm. According to WHO (2017) Maximum Permissible Limit (MPL) of EC (< 1500 uS/cm), all water samples are harmless to human health except to water samples (P1 and P5). Chloride concentration ranged between 110 and 213 mg/L showing that all water samples were within the upper limit (≤ 600 mg/L). The SO_4^{2-} concentration of water samples in this study area varied from 2.37 to 143 mg/L. All samples were below the MPL. The NO_3^- concentration in water samples ranges from 27 to 35 mg/L showing that all water samples were within the upper limit. For the remaining elements we notice the same thing with values below the MPL.

Table 1. *Analytical results for the different water points in mg/L except EC.*

Wells	T° (C)	pH	EC	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	PO_4^{3-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+
P1	16.5	6.3	1685	110	31	45	60	1.79	37	4.25	40	25	1
P2	16.6	6.8	1500	200	35	23.28	120	1.93	32	5.15	85	32.5	2
P3	19	6.5	991	125	29	2.37	135	3	27	4.28	55	25.5	1.5
P4	17.5	6.5	1081	125	27	7.7	80	2.7	27	3.32	52	16	0.3
P5	18	5.8	1643	150	30	70	60	4	33	5.15	78	25	0
P6	16.8	6.5	1050	142	29	51	90	1.65	22	4.36	85	29	0
P7	17	6.3	1129	135	27	109	85	1.65	27	4.28	73	31	0
P8	17.5	6.1	1068	130	33	37	65	2.44	33	4	60	22	0
P9	15.5	6.3	1077	135	28	60	70	2	28	5	64	26	1
P10	15.6	6.8	1400	149	28	143	125	3.25	33	5	100	34	0
P11	16.4	6.5	1279	156	31	50.5	105	1.81	31	4.2	80	28.5	0
P12	16.1	7	1436	213	28	99	170	1.7	134	35	64	23	0
Norm WHO (2017)	-	8.5	1500	600	50	400	-	5	200	12	200	150	0,1

4.2. Groundwater chemistry and water type

To identify and understand groundwater types and hydrochemical evolution in the study area, Piper diagram provides a very useful tool. This trilinear diagram is based on the concentration of various predominant cations and anions (Piper, 1944; Samaneh et al., 2018; Marghade et al., 2012). Figure 5 (presents the chemical analysis plot on this trilinear diagram. As shown in Fig. 4, in the lower left triangle, the samples plot mostly in zone B and A with only one sample in zone D, indicating that the groundwater in the study area is mainly of “non-dominant” and “calcium” types. The samples are mostly plotted in zone G with one sample in zone B in the lower right triangle, suggesting chlorite type. However, almost all samples are plotted in zone 1 with one sample in zone 2, indicating that groundwater in the study area is mainly of SO4 ·Cl–Na type and SO4·Cl–Ca·Mg type. These hydrochemical types are mostly connected to the dissolution of evaporated material found in gypsum deposits and the dissolution of carbonate-rich material.

4.3. Multivariate statistical analysis

4.3.1. Principal Component Analysis (PCA)

This is a **PCA correlation circle (factor map)** showing how variables relate to the first two principal components (PC1 = 29.11%, PC2 = 24.54%).

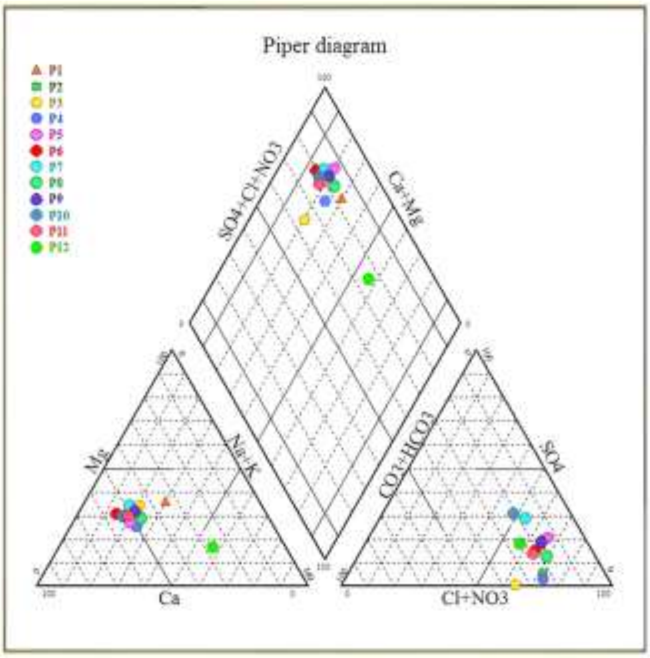

Figure 5. *Piper diagram of groundwater samples in study area.*

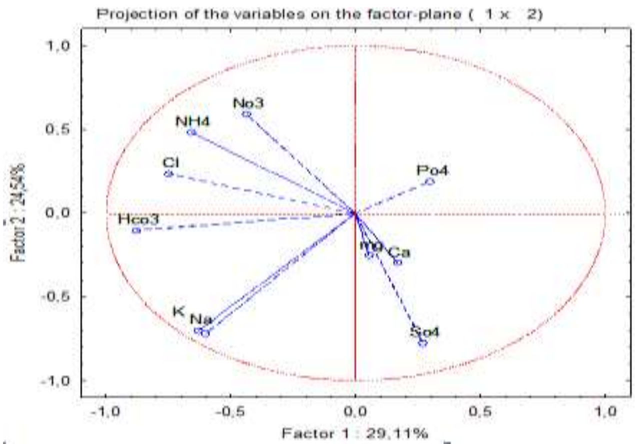

Figure 6. *Correlation matrix*

❖ **Two main opposing groups on PC1**

- Left side (negative PC1): HCO_3^- , Cl^- , NH_4^+ , NO_3^- , Na^+ , K^+
- Right side (positive PC1): SO_4^{2-} , Ca^{2+} , Mg^{2+} , PO_4^{3-}
- Na^+ and K^+ → strongly correlated
- Ca^{2+} and Mg^{2+} → also tightly grouped
- NH_4^+ and NO_3^- → moderately aligned

❖ **Variables close to the circle edge are best explained by PC1–PC2:**

- NO_3^- , NH_4^+ , SO_4^{2-} , Na^+ , K^+ , HCO_3^- Variables closer to the center (e.g., Ca^{2+} , Mg^{2+} , PO_4^{3-}) are less well captured by just these two components.

- PC1 (~29%): major chemical contrast (likely different water types or geochemical processes)

PC2 (~25%): secondary differentiation (possibly pollution vs natural mineralization)

❖ **PC2 may reflect a secondary gradient, possibly distinguishing:**

- nutrient/pollution signals (top)
- mineral/salinity-related signals (bottom)

Table 2 . *Equity (engiens values)*

Variables	Ca	mg	Na	K	Cl	Hco3	So4	No3	NH4	Po4
Ca	1,000000	0,846185	-0,076803	-0,020942	-0,243538	0,098608	0,338197	-0,026681	0,059050	0,163447
mg		1,000000	-0,123178	-0,077365	-0,230317	0,276029	0,394130	0,037775	0,244839	-0,065795
Na			1,000000	0,992435	0,305490	0,512542	0,288781	-0,165165	-0,019055	-0,232394
K				1,000000	0,239269	0,492375	0,277051	-0,199308	-0,010786	-0,251019
Cl					1,000000	0,542552	-0,173982	0,520091	0,438100	-0,004719
Hco3						1,000000	-0,118013	0,263436	0,702362	-0,251085
So4							1,000000	-0,380891	-0,568442	0,028528
No3								1,000000	0,476707	-0,082964
NH4									1,000000	0,024564
Po4										1,000000

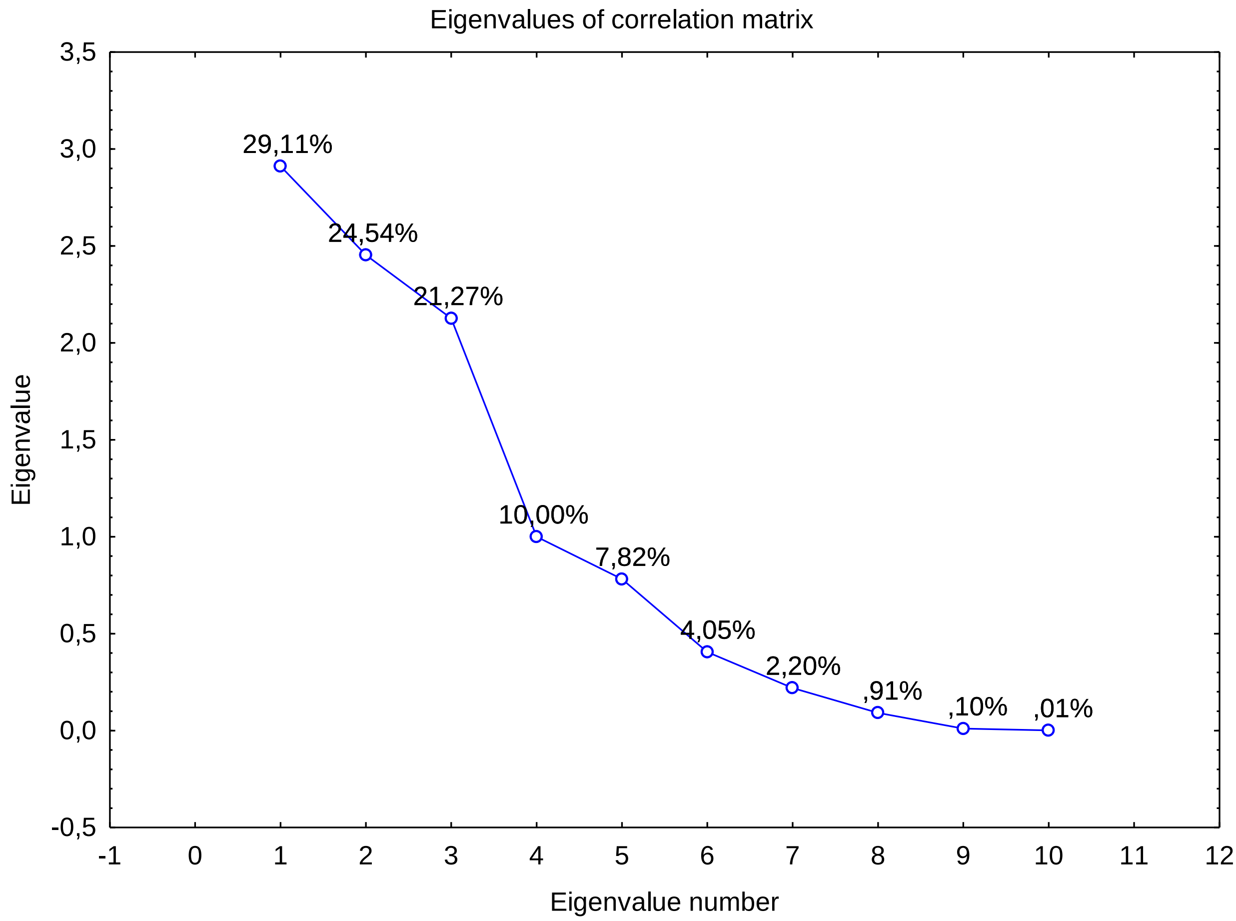

Figure 7 . *Distribution of wells*

This is a classic scree plot showing the eigenvalues (and explained variance percentages) from a correlation matrix—typically used in principal component analysis (PCA).

- **3 components**: good compact representation (major structure captured).
- **4 components**: better if you want a bit more accuracy without too much complexity.
- Beyond that: diminishing returns.

❖ **The first few components explain most of the variance:**
  - PC1: 29.11%
  - PC2: 24.54%
  - PC3: 21.27%

❖ **After the 3rd component, there's a noticeable drop:**
  - PC4: **10.00%**
  - PC5 onward: progressively much smaller contributions

❖ **There's a clear elbow around component 3 or 4:**

- Up to 3 components, you already explain about 75% of the variance.
- Including the 4th component brings you to about 85%..

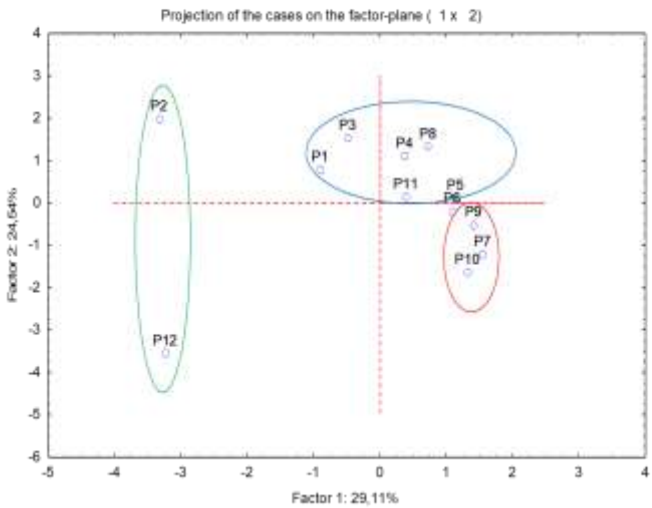

Figure 8 . *Correlation matrix*

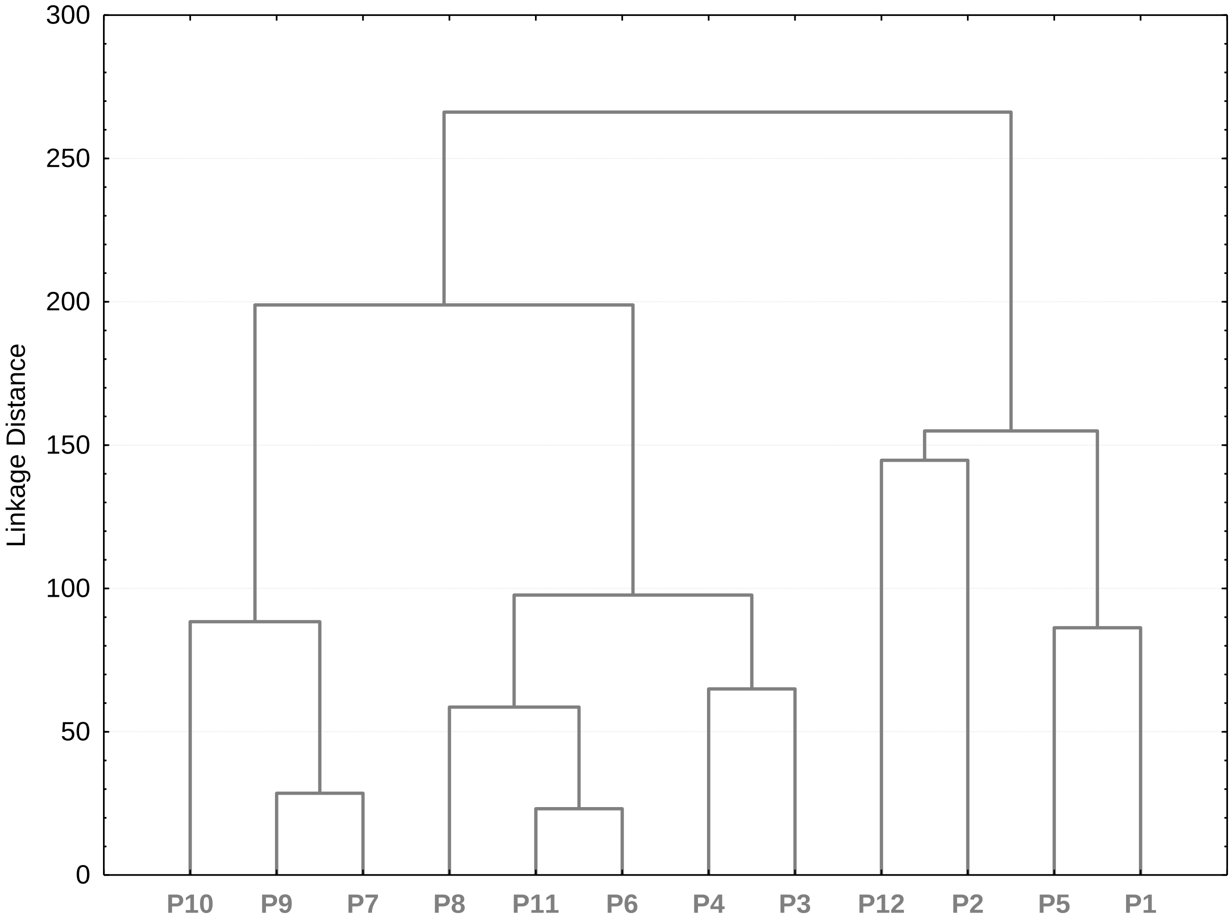

Figure 9. *Analyse AHC*

The PCR is performed using the previously interpreted parameters. It was discovered that the variation reflected by the factorial axes F1 and F2 is relatively substantial (66.37%) when observing the overall behaviour of the observations. Figure 9 shows the varimax rotational factor loadings of the primary components of the physicochemical characteristics of water sites within watersheds, illustrating the effect of physicochemical parameters on water resource quality in the study area. Every new variable shows how the same environmental conditions affect different aspects of water quality.

F1 had a maximum variance and explained 42.14% of the total variance, which is positively loaded on T° and moderately positive loaded on PO_4^{2-}. This factor is highly negatively loaded on: pH, TDS, EC, Cl^- Na^+, K^+, HCO_3^-, SO_4^{2-} and moderately negative loading on Ca^{2+}, Mg^{2+}, $NO_3^-$and NH_4^+.

F2 explained 24.23% of the total variance and contained strong positive loading of HCO_3^-, Na^+, K^+, pH, Cl^- and moderately positive loaded on NH_4^+. In addition this factor had a highly negative loaded on EC and moderate negative loaded on Mg^{2+}, NO_3^-, PO_4^{2-}, Ca^{2+} and SO_4^{2-}. Because of their close proximity to this axis, both elements are caused by the same phenomenon: rock dissolution and rainwater infiltration (recharge).

Those variables scattered clustering around the F1 and F2 axes demonstrates that both axes contribute to mineralization to varying degrees and take into consideration additional sources of mineralization.

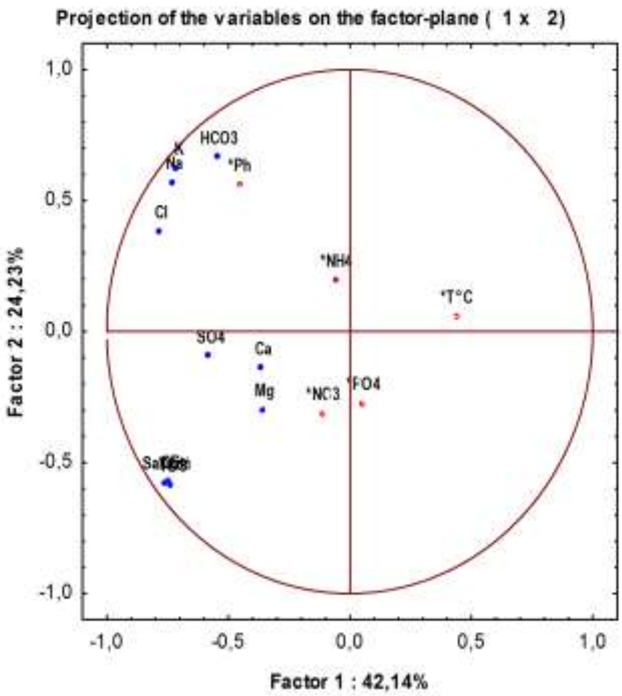

Figure 10 . *Analysis of variables in the F1–F2 factorial plane.*

This plot is a **PCA (Principal Component Analysis) variable projection circle** (also called a correlation

We have **main processes**:

1. Salinity / mineralization (Na, K, Cl, HCO_3)
2. Hardness / geology (Ca, Mg, SO_4)
3. Nutrients / environmental conditions (NO_3 , PO_4 , NH_4 , Temp, DO
4. Factor 1 (horizontal):
Opposes temperature vs mineral content (salinity/hardness)
5. Factor 2 (vertical):
Separates alkaline/salinity indicators (top) from hardness/nutrient/oxygen-related variables (bottom)

❖ **Axes**:
- Factor 1 explains **42.14%** of the variance
- Factor 2 explains **24.23%** → Together ≈ **66% of total variability**
- Distance from center: Variables near the circle edge are well represented by these two factors. Closer to the center = weaker representation
  - Angle between variables:
    - Small angle → positive correlation
    - Opposite directions → negative correlation
    - 90° → no correlation

  - **HCO_3^- , Na^+ , K^+ , Cl^-** cluster together (upper-left quadrant) → These variables are **positively correlated** and likely represent a **salinity / mineralization factor**.
  - **Temperature (*T°C*)** lies on the right side (positive Factor 1), opposite the salinity group → Suggests **temperature is negatively correlated with those ions**.
  - **NO_3^- , PO_4^{3-} , NH_4^+** are closer to the center/right → Moderate relationships, possibly forming a **nutrient/pollution gradient**, but weaker than the ion group.
  - **Ca^{2+} , Mg^{2+} , SO_4^{2-}** cluster in the lower-left → Likely represent a **water hardness / geological source factor**
  - **SatDO (and likely DO)** appear bottom-left → Negatively related to temperature (consistent physically: warmer water holds less oxygen).

4.3.2. Correlation matrix

Correlation coefficient is commonly used to measure and establish the relationship between two variables. It is a basic statistical tool for demonstrating the degree of dependence of one variable on another (Nyam et al. 2020). **Table 3** presents the results of the correlation matrix analysis. The examination of this correlation matrix indicates that it has established:
* Perfect correlation between sodium, potassium, chlorine and bicarbonate.
* A good correlation between sulphate, calcium, and magnesium.
* A moderate positive correlation between ammonia and nitrate
* A moderate negative correlation between ammonia and sulphate.

Table 3. *Correlation matrix on the global groundwater analyses of the study area*

	EC	Ca	Mg	Na	K	Cl	HCO_3	SO_4	NO_3	NH_4	PO_4
EC	1	0,08	0,2	0,30	0,22	0,34	-0,005	0,28	0,34	0,01	0,14
Ca	0,08	1	**0,73**	-0,11	-0,06	0,45	0,27	**0,53**	0,07	0,01	0,14
Mg	0,20	**0,73**	1	-0,18	-0,15	0,28	0,25	**0,51**	0,19	0,19	-0,15
Na	0,3	-0,11	-0,18	1	**0,99**	**0,67**	**0,63**	0,32	-0,14	-0,02	-0,23
K	0,22	-0,06	-0,15	**0,99**	1	**0,7**	**0,67**	0,33	-0,19	-0,01	-0,25
Cl	0,34	0,45	0,28	**0,67**	**0,7**	1	**0,69**	0,25	0,24	0,37	-0,2
HCO_3	-0,005	0,27	0,25	**0,63**	**0,67**	**0,69**	1	0,21	-0,1	0,46	-0,1
SO4	0,28	**0,53**	**0,51**	0,32	0,33	0,25	0,21	1	-0,4	**-0,5**	0,008
NO_3	0,34	0,07	0,19	-0,14	-0,19	0,24	-0,1	-0,4	1	**0,47**	-0,08
NH_4	0,01	0,01	0,19	-0,02	-0,01	0,37	0,46	**-0,5**	**0,47**	1	0,02
PO_4	0,14	0,14	-0,15	-0,23	-0,25	-0,2	-0,1	0,008	-0,08	0,02	1

4.3.3. Geochemical modeling

Generally, groundwater geochemistry is determined by the interactions between water and the aquifer matrix (Kaur et al., 2019). The saturation index calculation aims to forecast the mineral composition of reservoir rock without collecting samples (Appelo and Postma, 2004; Bouteraa et al., 2019). **Table 4** summarizes the results of the saturation index calculations for the selected minerals (Calcite, Dolomite, gypsum, and Halite). This table shows that all samples were below the equilibrium state indicating undersaturation with respect to those minerals, probably, this is due to evaporation in study area. In addition, For Dolomite, the values are too low, resulting in a fairly low saturation.

Table 4. *Saturation Index of different minerals using PHREEQC Software*

Wells	SI Calcite	SI Dolomite	SI Gypsum	SI Anhydrite
P1	-1.78	-3.97	-2.17	-2.39
P2	-0.69	-2	-2.21	-2.43
P3	-1.04	-2.62	-3.32	-3.54
P4	-1.3	-3.31	-2.8	-3.02
P5	-1.99	-4.69	-1.75	-1.97
P6	-1.11	-2.89	-1.86	-2.08
P7	-1.43	-3.43	-1.61	-1.83
P8	-1.78	-4.19	-2.1	-2.32
P9	-1.53	-3.66	-1.88	-2.1
P10	-0.65	-1.97	-1.41	-1.63
P11	-1.07	-2.79	-1.89	-2.11
P12	-0.49	-1.62	-1.73	-1.95

5.Conclusion

The objective of this study was to assess the origin of groundwater mineralization in the El Hadaiek aquifer and to characterize the geochemical facies using hydrochemical methods. The projection of analytical data on the Piper diagram revealed the presence of a sulphate–chloride magnesium–calcium facies. It also identified two distinct water types, which are consistent with both the spatial distribution shown in hydrochemical maps and the geological setting of the study area.The application of principal component analysis (PCA), particularly the F1–F2 axes, highlighted the significant contribution of rock dissolution processes and rainwater infiltration to groundwater mineralization.The analysis of the correlation matrix showed:

- A strong positive correlation between sodium, potassium, chloride, and bicarbonate.
- A good correlation between sulphate, calcium, and magnesium.
- A moderate positive correlation between ammonium and nitrate.
- A moderate negative correlation between ammonium and sulphate.

Furthermore, the saturation index calculations for selected minerals (calcite, dolomite, gypsum, and halite) indicated that all groundwater samples are undersaturated with respect to these minerals, suggesting that dissolution processes are still active. This undersaturation may be influenced by evaporation processes within the study area. In particular, dolomite exhibits very low saturation index values, indicating a notably low degree of saturation.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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