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Water resources and physicochemical properties of the Mio-Pliocene aquifer complex in the M'leta Plain, Western Algeria

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Abstract: The aquifers in the M'léta Plain are crucial for supplying drinking water and supporting industrial and agricultural water needs. However, they are facing a pollution risk and environmental degradation. The present study aims to assess the groundwater quality in the M'léta Plain, focusing on its physicochemical properties, statistics of the aquifer, pollution risks, and factors influencing the water mineralisation process. The analysis of 16 samples reveals that the water contains high levels of sulphates and chlorides, often accompanied by sodium, calcium, or magnesium. This suggests two distinct water types or facies: one characterised by sodium chloride or calcium chloride, and the other with calcic or sodic sulphate waters, sometimes including magnesium sulphate. These facies may be attributed to the influence of different formations at the outcrop.

Statistical analyses reveal a strong correlation between electrical conductivity and the majority of chemical elements, indicating the impact of freshwater interacting with the underlying rock formations on mineralisation. Some results also show undersaturation of certain minerals. Furthermore, the study evaluates the water's suitability for irrigation in the M'léta Plain in accordance with Richards' classification.

Keywords: aquifer, hydrochemistry, hydrogeology, Mio-Pliocene complex, pollution

INTRODUCTION

The study of groundwater hydrogeochemistry has garnered significant attention from numerous scientists, employing diverse methods such as hydrochemical analysis to assess water quality and pinpoint its sources (Baghvand *et al.*, 2010; Benziane, 2013; Bellaredj, 2016; Kheliel, Youcef and Achour, 2018). Groundwater's chemical composition is primarily influenced by the lithological composition of traversed layers it passes through and the residence time it spends there (Khedidja and Boudoukha, 2018), which affects the content of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} etc.). Climatic factors and anthropogenic activities further affect element concentrations through exchanges between aquifers and surface waters. With the increase in population and evolution of modern agro-industrial activities, threats to socio-economic development, particularly water resources (Castany, 1979) arise as various forms of pesticides and fertilisers are utilised. Mismanagement of these activities can lead to pollution, adversely affecting groundwater quality and rendering it unsuitable to meet demand and utilisation needs. The contamination risk exacerbated due to the absence of protective covers (impermeable formations), allowing pollutants direct entry into reservoir formations (Khedidja and Boudoukha, 2013; Khelifa, Khedidja and Hamidi, 2023). Groundwater pollution in the M'léta Plain aquifer is closely tied to poor management, excessive use of agricultural fertilisers, decomposition of organic matter, domestic wastewater, and industrial applications (Khedidja and Boudoukha, 2018). This study aims to comprehensively assess ground water quality in the M'léta Plain, particularly focusing on the physicochemical properties of the aquifer and associated pollution risks. Additionally, it underscores practical importance of sustainable management and the suitability of this water for societal needs. Through field campaigns and the collection of samples from the Mio-Pliocene aquifer, followed by physicochemical and statistical analyses, necessary data were gathered to understand its quality. Diagrams were used for water classification and to grasp the spatial evolution of hydrodynamic and chemical characteristics of groundwater in the region. This approach facilitated identifying mechanisms behind water mineralisation and pinpointing major factors controlling pollution sources. What distinguishes this work is its multidimensional approach, blending geochemical and statistical analyses to provide a comprehensive assessment of the aquifer's behaviour. The practical implications of this study extend beyond the M'léta Plain, as evident from its relevance to the broader discussion on sustainable water management and environmental conservation. This study's practical contributions resonate with broader global goals, including the UN Sustainable Development Goals, energy sustainability, emissions reduction, environmental conservation, cost-effective water management, climate change adaptation, and alignment with environmental, social, and governance (ESG) principles.

MATERIALS AND METHODS

THE STUDY AREA

The study area is located in the southern part of the endorheic watershed of the great Sebkha of Oran. Its boundaries are defined by the ridge of Mount Murdjadjo to the north, the foothills of Tessala to the South, the plateau of Oran–Es-Senia–Ain El-Beida to the East, and the town of Hammam Bouhadjar to the West (Fig. 1). Climatically, the region experiences a Mediterranean climate. Despite its proximity to the coast, it has a semi-arid climate, characterised by hot summers and relatively cold winters. The average temperature remains around 17°C, with annual rainfall not exceeding 374 mm at the Es-Senia station.

GEOLOGY AND HYDROGEOLOGY

The study area has experienced two major tectonic events, occurring along the boundary of the Tessala Mountains and within the M'léta depression (Gourinard, 1952). Additionally, minor tectonic events, typically oriented southward, often align with the existing hydrographic network. A significant collapse is evident from the reliefs of the Tessala Mountains and Mount Murdjadjo, revealing two smaller collapse basins beneath the sebkha and along the southern border of the M'léta Plain (Hassani, 1987). These two structures are separated by highly conductive shoals attributed to lower Miocene salt-bearing blue marls (see Fig. 2).

The facies began depositing primarily within the collapse basin of the M'léta Plain, originating from a Mesozoic substratum (Fenet, 1975; Thomas, 1985), predominantly composted of schists and quartzites. This substratum is overlain by a Cenozoic cover, consisting of blue marls (Middle Miocene), Tripoli limestones formations (Messinian), and reefal limestones. These formations crown the Tessala mountain, while recent formations (colluvium, alluvium) cover the whole plain of the great Sebkha of Oran (Fenet, 1975). These later formations are attributed to Pleistocene-Holocene formations and manifest as a stack of sandy-clay or silty subhorizontal layers (Thomas, 1985) – see Figure 3.

The hydrogeological study of the area has demonstrated that the formations comprising the Mio-Pliocene aquifer complex hold significant importance. These formations, primarily composed of limestone and sandstone, are notable for their extensive outcrop, large extension, and favourable fracturing for storage, particularly in the case of limestone. These characteristics make them well-suited for storing and facilitating groundwater

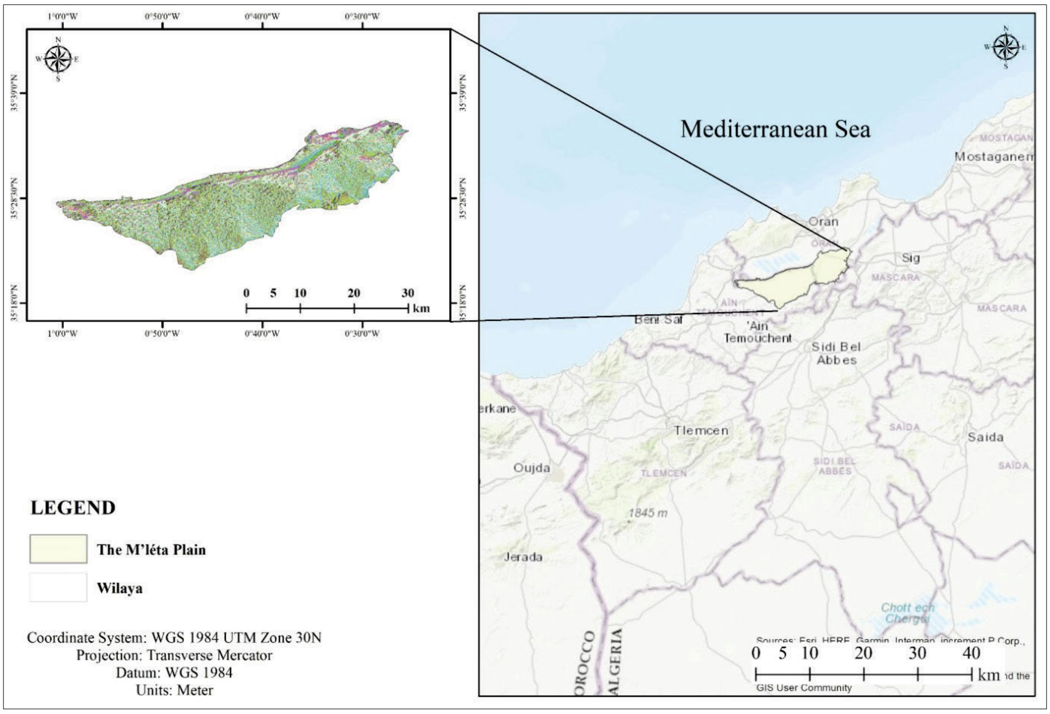

Fig. 1. Study area location; source: own elaboration

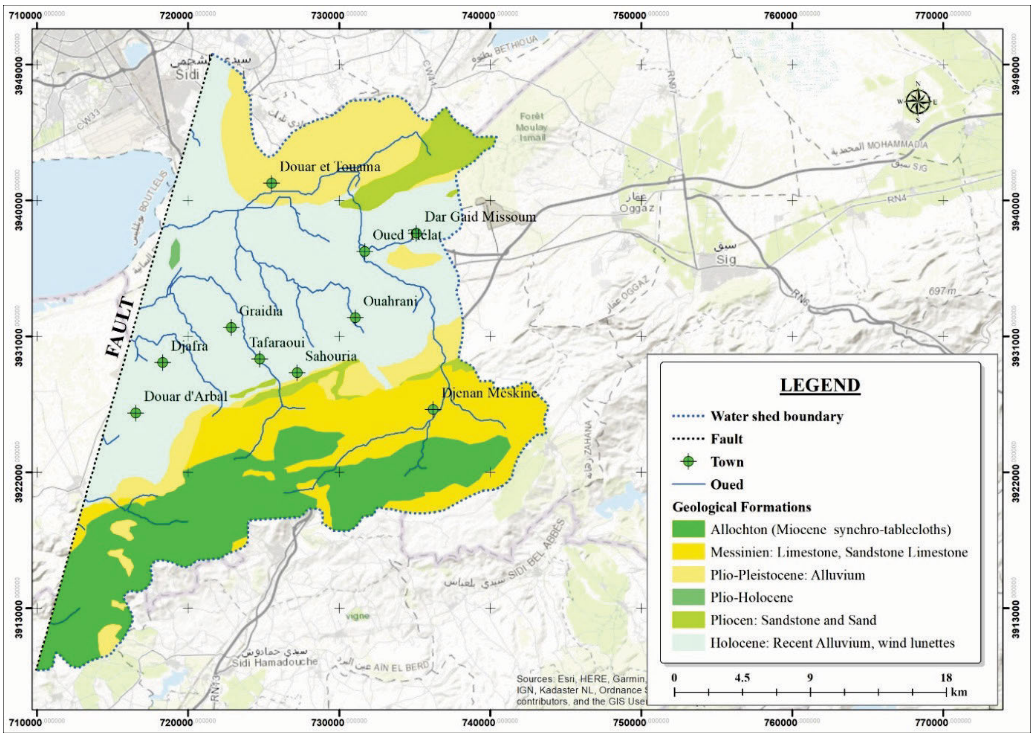

Fig. 2. Geological and structural map of Oranie; source: own elaboration

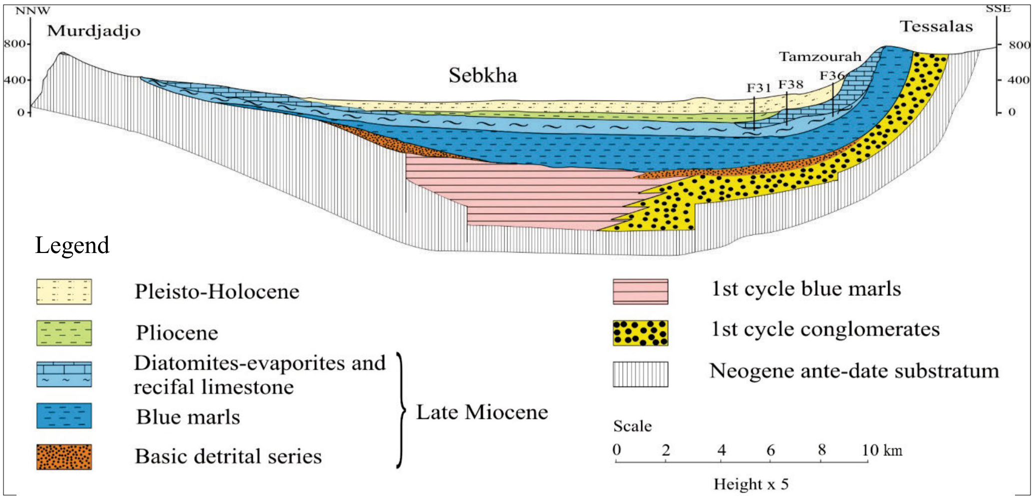

Fig. 3. Interpretative hydrogeological section of the basin of the great Sebkha of Oran; source: Hassani (1987), modified

circulation. The infiltration waters are stopped downward by the intercalations of the Tripoli marly levels or by the blue marls (Hassani, 1987; Bellaredj, 2016). While attention continue to focus on the deep aquifers that yield positive results, it is important to emphasise the necessity to avoid overexploitation of these aquifers due to their slow and challenging recharge process (Bouazza, 2014).

Based on Figure 4, the initial conditions indicate that the piezometric level of the aquifer ranged between 106–168 m during rest, as detailed in Table 1. Upon commencement of the pumping process, a cone of depression formed in the aquifer. The data suggest that during pumping, the piezometric level or water table decreased to a range between 15–30 m, indicating the direct impact of pumping on groundwater levels and leading to a lowering of the water table near the well. The observed changes in the aquifer's piezometric level highlight the importance of

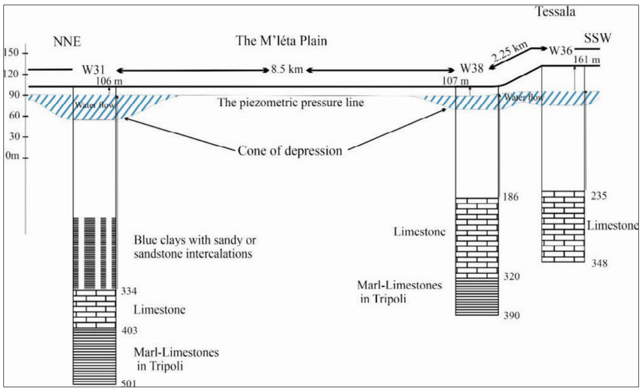

Fig. 4. Load of the water table in relation to the aquifer formations of the M'léta Plain; source: own elaboration

Table 1. Characteristics of a carbonate aquifer captured by drilling in the M'léta plain

Well	Embere coordinate			Piezo-meter level (m)	Depth (m)	Cone of depres-sion (m)
	X	*Y*	*Z* (m)			
W 31	206,870	254,550	104	106	501	34
W 36	201,530	245,890	161	161	348	15
W 38	200,890	247,560	107	107	390	20

Source: own elaboration.

understanding and monitoring groundwater dynamics, especially during pumping operations. Such information is critical for assessing the sustainability of groundwater extraction, preventing excessive pumping, and effectively managing potential impacts on the aquifer and surrounding ecosystems.

STUDY METHODS

The hydrochemical analysis covered 16 samples collected from the well-positioned Mio-Pliocene aquifer in the region (Fig. 5). The study was staged.

Following the field campaign sampling, three physico-chemical variables (temperature, pH, and *EC* – electrical conductivity) were promptly measured *in situ* using a multi-parameter instrument (Multi 350i/SET). Subsequently, the samples were meticulously poured into plastic bottles (1.5 dm^3) and transferred to the laboratory using a cooler to maintain their temperature. Upon reaching the laboratory, the samples were stored in a refrigerator at –4°C before undergoing chemical analysis. This meticulous procedure was implemented to uphold the preservation and integrity of the groundwater samples, ensuring their accurate subsequent analysis.

These samples were analysed in the laboratory of ADE (Water Distribution Company), Relizane, in the periods of 7–12 February 2021 and 21 June 2021. The analyses specifically focused on the following major chemical ions:

- cations: Ca^{2+}, Mg^{2+}, Na^+ and K^+;
- anions: $Cl^–$, $SO_4^{2–}$, $HCO_3^–$ and $NO_3^–$.

SUITABILITY OF WATER TABLE FOR IRRIGATION PURPOSES

In our study, the assessment of irrigation water quality is crucial, with significant implications for agricultural production and soil physico-chemical properties (Suarez, Wood and Lesch, 2006). In arid areas, the excessive and discriminate use of irrigation water results in the accumulation of salts in the soil, which hampers plant growth (Masmoudi, 2016). Consequently, studying irrigation water classification becomes essential for evaluating the impact of water mineralisation on both soil and crops. Richards proposed a diagram correlating the sodium absorption rate (*SAR*) and the electrical conductivity of water (Richards (ed.), 1954). The *SAR* is defined by the following equation, measured in concentration units of meq·$dm^{–3}$.

$$SAR = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca} + \mathrm{Mg})/2}} \tag{1}$$

RESULTS AND DISCUSSIONS

PHYSICAL PARAMETERS

Water temperature

The temperature of water plays an important role in the solubility of gases, especially oxygen. Warmer water holds less oxygen in solution, and the depletion of oxygen is a key indicator of thermal pollution. Temperatures above 15°C can have a negative impact

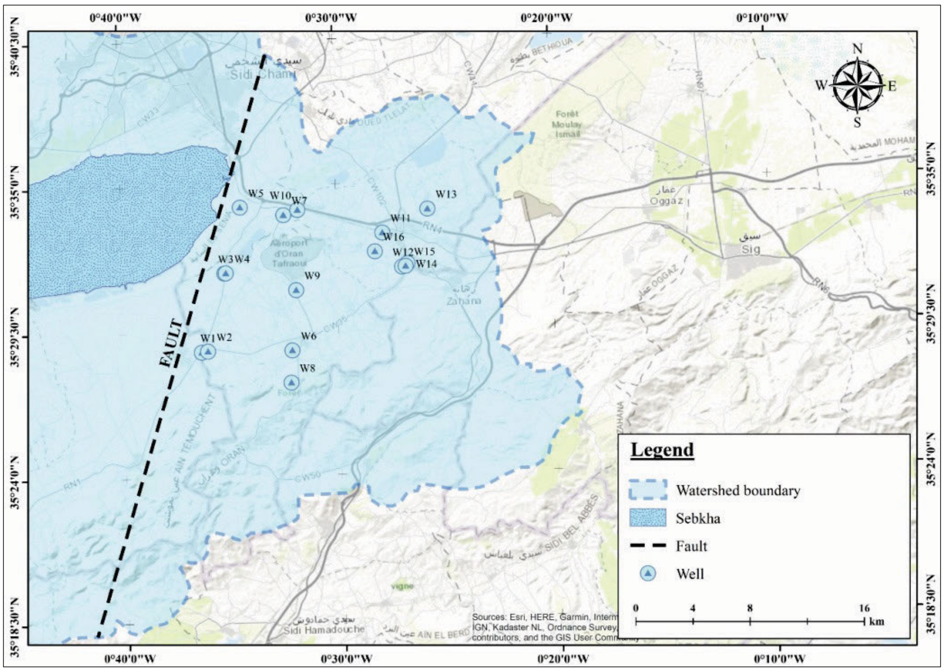

Fig. 5. Location of water points; source: own elaboration

on human health, fostering growth of pathogenic microorganisms and exacerbating fermentation, which further reduces the content of "dissolved oxygen". Sudden changes in water temperature raise concerns about water quality and questions about mixing with water from other sources.

During the sampling campaign in February and June 2021, the water temperature in the study area varied from 19 to 23°C.

Hydrogen potential

The pH of water indicates its acidity or alkalinity and plays a crucial role in adjusting the physico-chemical balance, in particular the calcium-carbonate equilibrium, which affects water's interaction with carbonates, either corroding or depositing them. Water from sandy or granite aquifers tends to be acidic, while in limestone aquifers, it tends to be alkaline. The levels of pH are adjusted as necessary by removing excess dissolved CO_2 or by correcting carbonate hardness.

The measured pH values, ranging from 7.2 to 7.6, indicate a slightly basic pH. The pH measurements confirm that all the boreholes fall within the potability standard range.

Electrical conductivity

Water conductivity reflects the degree of mineralisation, corresponding to the presence of ionic species in the water, with higher concentrations of dissolved salts leading to increased conductivity. The conductivity values of our aquifer have been measured both on-site and in the laboratory, expressed in $\mu S \cdot cm^{-1}$, ranging between 1678 and 4813.

The variation may have several causes:

- geological zoning and water exchanges in the surrounding area;
- general direction of groundwater flow;
- exchanges between different aquifers, particularly in boreholes with poor cementation;
- significant evaporation caused by the proximity of the water table to the surface.

During the winter season, water levels typically rise due to the precipitation infiltration, resulting in a decrease in the concentration of chemical ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-}). Conversely, when water levels are low, the concentration of these chemical ions increases to reduced meteoritic inputs and increased evaporation, which elevates the concentration of dissolved ions.

THE PROCESS OF MINERALISATION

Statistical analysis

Given the extensive dataset and its notable variability, the principal component analysis (PCA) was selected for the statistical analysis. The PCA is reknowned for its sensitivity to extreme values and is widely considered an ideal technique due to its algebraic simplicity and straightforward interpretation. Its primary objective is to comprehend aquifer functioning and unveil the mechanisms underlying water mineralisation. The PCA functions as a projection method, transforming n samples from the p-dimensional space characterised by p variables into the k-dimensional space (where $k < p$) while preserving as much information as possible. In this multidimensional space, all samples collectively form a cloud of points. To mitigate the impact of size and data heterogeneity, the data are centred and reduced before analysis.

The sample set allows to visualise results and interpret their arrangement. The analysis helps to understand correlations between variables in pairwise comparisons, selecting different factorial axes, determining each variable contribution to the formation of factorial axes, and to understand various mechanisms involved in groundwater mineralisation.

The varimax rotation was performed on the main components to facilitate the interpretation of factors according to the natural or anthropogenic processes controlling water mineralisation. The study included the PCA performed on all 16 groundwater samples from El Golea. It focused on reduced centred variables using the Statistica 13.4.0 software package (TIBCO Statistica 2018) software. Ten variables such as physico-chemical parameters (pH, *EC*, TDS) and major ions, including Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-}, were considered.

The cluster analysis includes a set of statistical techniques that are used to determine natural statistical data groups and patterns. It is a commonly used multivariate method to provide hydrochemical water data analysing that complements the PCA. The mathematical foundation of the method is based on the calculation of the Euclidean distance between individuals or observations in an n-dimensional space. The short Euclidean distance indicates a strong similarity between objects measured. The graphical representation of clustering or hierarchical aggregation and the corresponding distance to determine correlation is called a dendrogram. Specific groups and hierarchical cluster analysis (HCA) groups were used to provide a comprehensive interpretation of the chemical data concerning nine chemical variables (*TDS*, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO_3^{-}) and 16 groundwater samples, respectively.

Correlation matrix

Correlation is a statistical method applied to describe the relationship between two variables. The correlation coefficient quantifies the strength and direction of a linear relationship between them. When the correlation coefficient is close to 0, it suggests a weak or no relationship between the variables. As the correlation coefficient approaches –1 or 1, it suggests a stronger relationship between the two variables, either negatively or positively correlated.

In the examination of the 16 samples from the Moi-Pliocene aquifer of the M'leta Plain, the correlation matrix in Table 2 reveals a very strong correlation between electrical conductivity (*EC*) and most of the chemical elements, with the exception of calcium, potassium.

Circle of correlation and individual projection

By applying the principal component analysis (PCA) on the selected variables (*EC*, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, HCO_3^{-} and NO_3^{-}) presented in Table 2, we enhance and deepen our understanding of the main factors that determine mineralisation mechanisms across all water samples. The interpretation of the PCA is based on to the sequence in which the results appear in the software.

The correlation circle drawn at the level of the factorial axes F1 and F3 (Fig. 6) displays a favourable distribution of the parameters. The first two axes, F1 and F3, account for 44.00% and 14.36% of the total variance, respectively. The primary axis of

Table 2. Correlation matrix for different water points

Variable	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	*EC* ($\mu S \cdot cm^{-1}$)	*TDS* ($mg \cdot dm^{-3}$)	pH
	$mg \cdot dm^{-3}$										
Ca^{2+}	**1**										
Mg^{2+}	0.0211	**1**									
Na^+	0.1309	**0.5275**	**1**								
K^+	0.3361	−0.2647	0.1805	**1**							
HCO_3^-	0.2298	0.3600	0.2024	−0.1639	**1**						
Cl^-	0.0644	0.4819	**0.8611**	−0.0330	−0.0444	**1**					
SO_4^{2-}	**0.6855**	**0.5746**	0.3986	0.2240	0.3838	0.1500	**1**				
NO_3^-	0.1784	0.0132	0.1067	−0.0998	−0.1775	0.2539	−0.0196	**1**			
EC	0.3406	**0.7740**	**0.8731**	0.0545	0.3327	**0.7743**	**0.6942**	0.1424	**1**		
TDS	0.4819	**0.7132**	**0.8049**	0.1227	0.4283	**0.6515**	**0.7986**	0.1349	**0.9682**	**1**	
pH	−0.1391	−0.2988	−0.2662	0.1883	−0.2168	−0.1431	−0.3222	0.2465	−0.2844	−0.2757	**1**

Explanations: *EC* = electrical conductivity, *TDS* = total dissolved solids; 1 means that there is a 100% complete relationship, bold values are close to 1, it means that there is a strong relationship between the variables.
Source: own study.

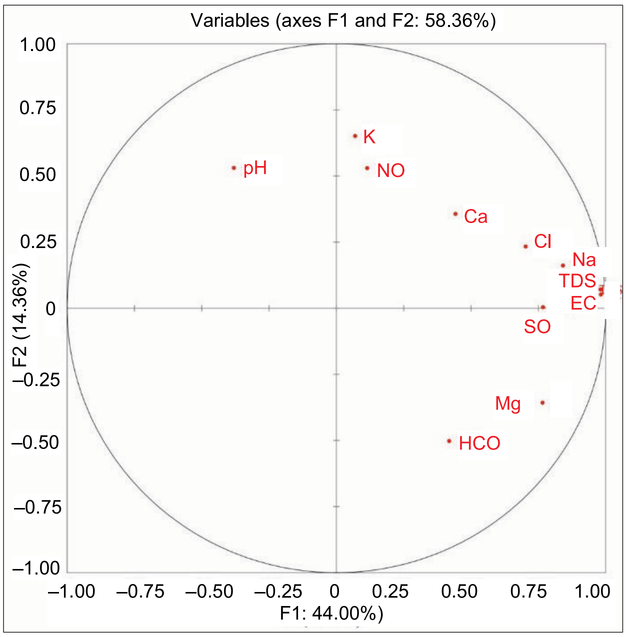

Fig. 6. Correlation circles for factors F1–F2; source: own study

inertia, F1, exhibits positive loading on all variables. This factor indicates that the *EC* is associated with the hardness of calcium, magnesium, sodium, potassium, bicarbonates, chlorides and sulphates, suggesting potential water-rock interactions. Axis F1 reflects both mineralisation and organic pollution of the water. On the other hand, the second axis, F3, is closely associated with sodium and potassium and pH in the positive side, while linked with bicarbonates and magnesium on the negative side. This axis represents lower water mineralisation compared to axis 1.

The interpretation of the correlation circle facilitates our understanding how the original variables contribute to the principal components. Consequently, it highlights the underlying factors influencing the mineralisation of water in the Mio-Pliocene aquifer of the M'leta Plain.

Hierarchical cluster analysis

The results of the hierarchical ascending classification for 16 samples are presented by the dendrogram in Figure 7. The HCA supports the results of the PCA by showing three distinct groups.

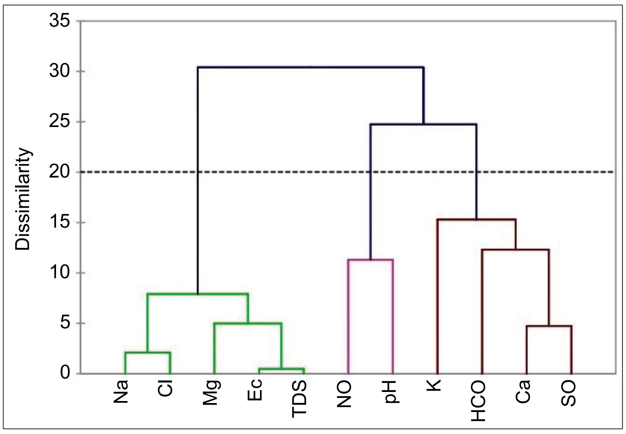

Fig. 7. Dendrogram of examined variables; source: own study

First group: this group shows the relationship between Na^+, Cl^-, Mg^{2+}, SO_4^{2-}, *TDS*, and *EC* (Fig. 7). This is indicative of the aquifer salinity, suggesting a commonality in the salinity characteristics among the samples in this cluster.

Second group: it combines NO_3^- and pH, indicating a relationship between sample acidity and bicarbonate content. This suggests that samples within this cluster share similar characteristics regarding acidity and bicarbonate levels.

Third group: the third group shows the relationship between K^+, Ca^{2+} and HCO_3^-.

In summary, the dendrogram provides a clear visual representation of how the samples group together based on their hydrochemical characteristics, offering valuable insights into the distinct relationships among different parameters in the Mio-Pliocene aquifer of the M'léta Plain.

CLASSIFICATION OF THE WATERS OF THE MIO-PLIOCENE COMPLEX

To delineate the various hydrochemical facies of water encountered in our region and gain insight into the qualitative aspect of groundwater, we used the Diagram 2.0 software as an essential tool. To accomplish this objective, we employed a classification diagram, based on the graphical distribution of major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and major anions (HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO_3^{-}) within the triangular diagram proposed by Piper (1944).

The interpretation of the hydrochemical analysis results using the Piper diagram provided an overview of the chemical facies of the Mio-Pliocene aquifer in the M'léta Plain (Fig. 8).

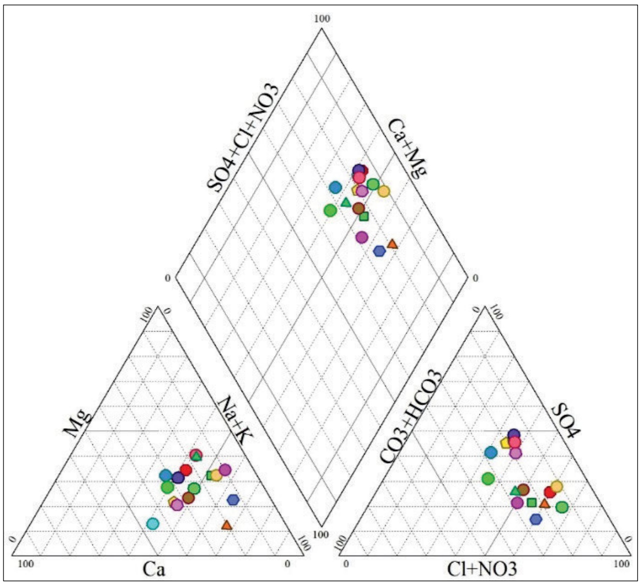

Fig. 8. Piper diagram of the Mio-Pliocene complex aquifer of the M'léta plain; source: own study

The interpretation of the point clouds on the Piper diagram suggests the prevalence of a relatively dominant calcium chloride facies in the hydrochemical composition of the Mio-Pliocene aquifer in the M'léta Plain. Additionally, a small percentage of boreholes exhibit characteristics associated with a sodium chloride facies. This information provides valuable insights into the predominant water types and their chemical composition in the aquifer, helping to characterise the hydrochemical facies present in the studied region.

GEOCHEMICAL MODELLING

By calculating the saturation index (*SI*), we can predict the mineral aspect of the solid matrix of the reservoir rock without the need to take samples from it (Bouteraa *et al.*, 2019). Additionally, the *SI* allows us to determine the effect of chemical elements on water chemistry. The degree of water saturation can be represented by Equation (1):

$$SI = \log(IAP/\mathrm{K_{SP}}) \tag{2}$$

where: IAP = ion activity product (product of the activities or concentrations of the ions in solution raised to the power of their stoichiometric coefficients in the equilibrium expression), K_{SP} = constant characterises the equilibrium established in a reversible system which ceases to evolve (for a given temperature).

Note that the *SI* will be zero, positive, and negative, respectively, for a solution in equilibrium with the mineral solid phase considered, for oversaturation and for undersaturation with respect to some minerals.

The saturation indices were computed using the Diagram-software, and the results have been organised and presented in Table 3. Additionally, graphical representations of the results are provided in Figure 9.

Table 3. Evolution of mineral saturation indices using PHREEQC software

Well	Carbonate minerals			Evaporitic minerals		
	SI calcite	*SI* aragonite	*SI* dolomite	*SI* gypsum	*SI* anhydrite	*SI* halite
W 1	0.23	0.08	0.31	−1.18	−1.41	−5.17
W 2	−0.34	−0.48	−0.26	−1.69	−1.92	−5.83
W 3	0.07	−0.08	−0.01	−0.70	−0.94	−5.58
W 4	−0.31	−0.46	−0.32	−1.88	−2.12	−5.70
W 5	0.34	0.20	0.57	−0.70	−0.93	−5.45
W 6	0.10	−0.05	0.43	−1.03	−1.27	−5.30
W 7	0.54	0.39	0.58	−0.55	−0.79	−5.57
W 8	0.24	0.09	0.59	−1.07	−1.31	−5.13
W 9	0.06	−0.09	0.28	−0.68	−0.90	−5.47
W 10	0.47	0.32	1.02	−0.82	−1.05	−5.78
W 11	0.24	0.09	0.93	−0.75	−0.99	−5.19
W 12	0.26	0.11	0.49	−1.06	−1.30	−5.90
W 13	−0.18	−0.32	0.11	−1.08	−1.32	−5.00
W 14	−0.06	−0.21	0.49	−1.52	−1.76	−5.32
W 15	0.23	0.08	0.45	−0.88	−1.12	−5.23
W 16	0.10	−0.05	0.65	−1.36	−1.60	−5.64

Source: own study.

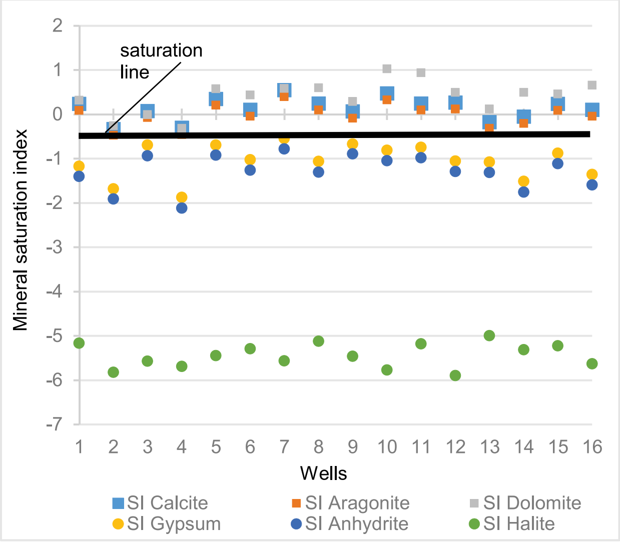

Fig. 9. Variation of the saturation index of the indicated minerals: carbonate minerals, gypsum, and halite; source: own study

Table 3 shows that the carbonate minerals calcite and dolomite have positive saturation values in most wells, indicating an oversaturation relative to these two minerals and a tendency towards precipitation. The main reason for these precipitations can be explained by the aridity characterising the study area with an aridity index of 12.47 (De-Martonne index), intense evaporation of 1389 mm·y^{-1} and a decrease in annual rainfall of 374 mm. On the other hand, the evaporitic minerals, gypsum and halite, are approaching their equilibrium. All *SI* values are negative, indicating undersaturation with respect to these minerals. The lower concentration of Na compared to Cl is probably due to the fact that Na can bind clay minerals through the process of ion exchange.

QUALITY OF IRRIGATION WATER BASED ON SODIUM ABSORPTION RATE

Through Richards' proposed diagram regarding sodium absorption rate (SAR) and water electrical conductivity (Richards (ed.), 1954) – Figure 10, three different sections are delineated.

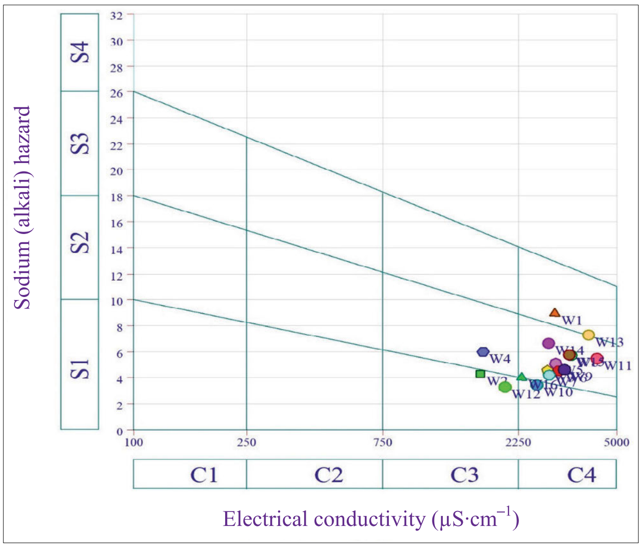

Fig. 10. Irrigation water quality based on sodium adsorption ratio; S1 = low sodium hazard, S2 = medium sodium hazard, S3 = high sodium hazard, S4 = very high sodium hazard, C1 = non-saline, C2 = slightly saline, C3 = moderately saline, C4 = very saline; source: own study

C3-S1, C3-S2: these two classes present water of acceptable quality, suitable for irrigation. However, a control of the evolution of salinity is recommended. Three water points of this class have been identified, i.e. 18.75% of the total.

C4-S1, C4-S2: these two classes are characterised by a poor and highly mineralised water quality, which may be suitable for the irrigation of certain species that are very tolerant to salt and on well-drained and leached soils. Twelve water points from this class were recorded, i.e. 75% of the total.

C4-S3: this class has poor water quality and are not suitable for irrigation, but can be used under certain conditions: very permeable soils, good leaching, very salt-tolerant plant. We only have one sample in this class.

Summarising, this study encapsulates major findings, shedding light on the in-depth geochemical and statistical analyses of the aquifer system in the M'léta Plain and highlighting key aspects of water mineralisation and its association with geological formations. However, the study distinguishes water types adding a novel dimension to the existing body of knowledge and enriching our understanding of aquifer behaviour. It is essential to acknowledge the limitations of this study, as it includes the relatively small sample size, potential sampling biases, and the absence of detailed consideration of external environmental factors. These limitations may impact the possibility to generalise the findings and suggest opportunities for future research with more extensive data and interdisciplinary approaches. However, through these findings, stakeholders can leverage the research to promote sustainable engineering practices, develop effective regulations and policies, advance energy systems, and incorporate environmental, social, and governance (ESG) considerations into financial and investment decisions. Ultimately, this contributes to the broader goal of achieving sustainable and responsible development in the M'léta Plain and beyond.

POLICY RECOMMENDATIONS

Building on our findings, we propose several feasible policy recommendations:

- implement a comprehensive and ongoing monitoring system for the aquifer system to capture temporal variations and improve data quality;
- develop sustainable water resource management policies that consider the complex interplay between geological factors and water quality parameters;
- establish robust regulations and standards that safeguard the aquifer's quality and promote the sustainable use of this vital resource;
- integrate environmental impact assessments into aquifer management, considering factors such as land use, pollution sources, and climate change impacts;
- encourage adaptive management practices that account for uncertainties in climate change projections and evolving scientific knowledge.

These policy recommendations can support more informed decision-making, regulatory frameworks, and sustainable practices for the responsible management of the M'léta Plain aquifer system and provide a template for other regions with similar geological and hydrogeological characteristics.

CONCLUSIONS

Considering the hydrogeological context presented for the M'léta Plain, the Miocene limestone formations emerge as the primary aquifer of interest due to their extensive coverage both at the outcrop and in depth, the significant thickness, and favourable fracturing conducive to water storage. This aquifer is limited in the upper layers by either the red marls of the lower Pleistocene, or the blue-brown marls of the marine lower Pliocene, forming an effective barrier against surface pollution.

Our research delved into the geochemical aspect, highlighting the relationship between geology and aquifer hydrochemistry. The analysis of the data utilising different methods revealed that the Mio-Pliocene aquifer waters exhibit temperature gradients ranging between 19 and 23°C, while the pH of all the wells falls within the potability standard range. Chemical elements concentrations tend to decrease during the winter season, correlating with an increase in water level, and vice versa. Two dominant chemical facies emerged: calcium chloride and sodium chloride. Additionally, multivariate statistical analysis confirmed a very strong relationship between electrical conductivity and most of the investigated chemical substances, with nitrates potentially of anthropogenic origin, possibly stemming from agricultural use of fertilisers. Saturation index analyses sometimes indicated undersaturation with certain minerals. In terms of water quality, it generally ranges from poor to acceptable for irrigation.

This research has significantly enhanced our understanding of the geochemical and statistical analyses of the M'léta Plain aquifers. The findings have provided substantial support for our initial hypothesis, which aimed to comprehend the aquifer's behaviour. What distinguishes this work is its multidisciplinary approach and the delineation of water types based on geological formations, offering new insights into aquifer systems. Moreover, this analysis also has global significance, offering practical implications for diverse stakeholders. Industries can benefit from adopting sustainable practices, while countries and regions can develop effective regulations and policies for water resource management. Policymakers can make informed decisions grounded in scientifically established standards and targets.

The results of this study have far-reaching implications for aquifer systems worldwide extending beyond the M'léta Plain.

Building on this research, several avenues for future work emerge:

- a long-term monitoring programme should be established to capture seasonal and interannual variations in water quality; this data will help refine our understanding of aquifer dynamics over time;
- future research can delve deeper into the influence of land use, pollution sources, and climate change on the aquifer system to provide a holistic understanding of the environmental factors affecting water quality;
- collaboration with climate scientists to integrate aquifer behaviour data with climate models can enhance the accuracy of climate change projections, particularly in regions that depend on groundwater resources;
- interdisciplinary research involving geologists, hydrologists, chemists, and environmental scientists can create a comprehensive model of aquifer systems and their interactions with the environment;
- comparative studies of aquifer systems in other regions worldwide can explore similarities and differences, facilitating the development of best practices in aquifer management.

By addressing these future research areas, we can further refine our understanding of aquifer systems, contribute to more effective policy and management, and advance global efforts to achieve sustainable water resource use and environmental conservation.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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