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Assessment of the physico-chemical quality of groundwater from the central Middle Atlas in a context of intensive agriculture: the case of the Timahdit-Guigou plain

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Abstract: The Timhadit-Guigou plain contains a groundwater table, constituting a significant hydraulic heritage for the region and Morocco. This resource serves as the sole source of drinking water for the local population. However, the recent development of intensive agriculture in the area exposes this table to an increased risk of contamination from agricultural sources. This study assesses groundwater's physicochemical quality from certain wells and springs for human consumption. To do this, several physical and chemical parameters were analyzed, including those related to anthropogenic activities: temperature (°C), pH, electrical conductivity (µS/cm), dissolved oxygen (mg/L), ammonium (NH_4^+), nitrates (NO_3^-), total nitrogen, orthophosphates (PO_4^{3-}) and total phosphorus. The Water Quality Index (WQI) was applied to assess the overall water quality. The results show that some sites have high nitrogen levels and acidity exceeding the thresholds permitted by the WHO (2011, 2017). The water quality index ranges from 13.58 to 64. The overall index indicates that the waters are generally potable, although two stations have poor water quality, which could represent a risk to the population's health.

1. Introduction

Water resources are degrading at an alarming rate globally (Gleick, 2020). Their use for agricultural production has significantly contributed to the deterioration of their quality and quantity, particularly in arid and semi-arid regions (Scanlon *et al.,* 2017). Morocco is among the countries where agriculture is a key economic pillar. In this context, groundwater is becoming an increasingly crucial factor for the sustainability of agriculture (DGH, 2000; Karimi *et al*., 2022; Quandt *et al.,* 2023; Karandish *et al.,* 2025). However, intensive agriculture in irrigated areas significantly contributes to diffuse groundwater pollution (Soudi *et al.*, 1999; Alaqarbeh *et al.,* 2022; Boutebib *et al.*, 2023). Physicochemical analyses conducted from 2007 to 2008 for groundwater tables throughout Morocco revealed that the overall quality of groundwater was good for 28% of stations, average for 28%, and degraded for 44% (MEMEE-SEEE, 2008).

The Middle Atlas, often called the "Water Reservoir of Morocco," was once considered a land of cattle breeding (Jennan, 1986). It has become a center for producing vegetable crops and rosaceae, both regionally and nationally. The agricultural area now covers 34,900 hectares in the interior depressions (Aoua, Laanoucer, Ifrah, Guigou …) (Lazhar, 2024). This agricultural dynamic is increasingly concerning regarding the quality of groundwater in this environment, which is already vulnerable to pollution due to the high permeability of the substrate (Martin, 1984). In this context, this study aims to evaluate the physicochemical quality of the groundwater in the Guigou Plain, a component of this mountainous area. The groundwater aquifer of the Timahdit - Guigou plain is one of the most significant aquifers in the Middle Atlas. In addition to the region's dominant permeability, the plain's geographical location allows it to benefit from the fluxes originating from the Pleated Middle Atlas and Tabular Middle Atlas.

The literature survey collected using Scopus on “Groundwater and quality” comprises more than 50,400 articles and is reduced to over 3,000 when “physicochemical” is added to the previous keywords. The net increase in articles over the last decades reveals the importance of water supply to populations and the agricultural sector (**Figure 1**). A bibliometric analysis consolidates several published works to draw indicators, such as global production, the most prolific authors and countries, and cooperation (Donthu *et al.*, 2021; Velez-Estevez *et al.*, 2022; Laita *et al.*, 2024; Kumar, 2025; V *et al.*, 2023;). Scopus analysis may be shown by histograms and VOS viewer mapping, also called clusters, where the authors or countries are presented by a colored node whose diameter indicates the number of articles (Orduña-Malea & Costas, 2021; Kirby, 2023; Chakir *et al.*, 2023; Nandiyanto *et al.*, 2024; Hammouti *et al.*, 2025).

Figure 2 allows us to distribute this production by field; we can easily see that the fields of environmental science (~40%), Earth and Planetary Science (~13%), and agriculture (~11%) are dominant, etc. It’s also noted that over (~90%) of published documents are articles and 5.6% as conference papers (**Figure 3**). Since its introduction by Waltman et al., 2010, VOSviewer software has received more attention from researchers and policymakers to estimate qualitatively and quantitatively the research production of authors, laboratories, and countries, including co-occurrence analysis and visualization clustering. Among the 149 countries gathered, India is represented by the largest dark purple node, indicating its high concern for securing safe water for its citizens and agriculture.

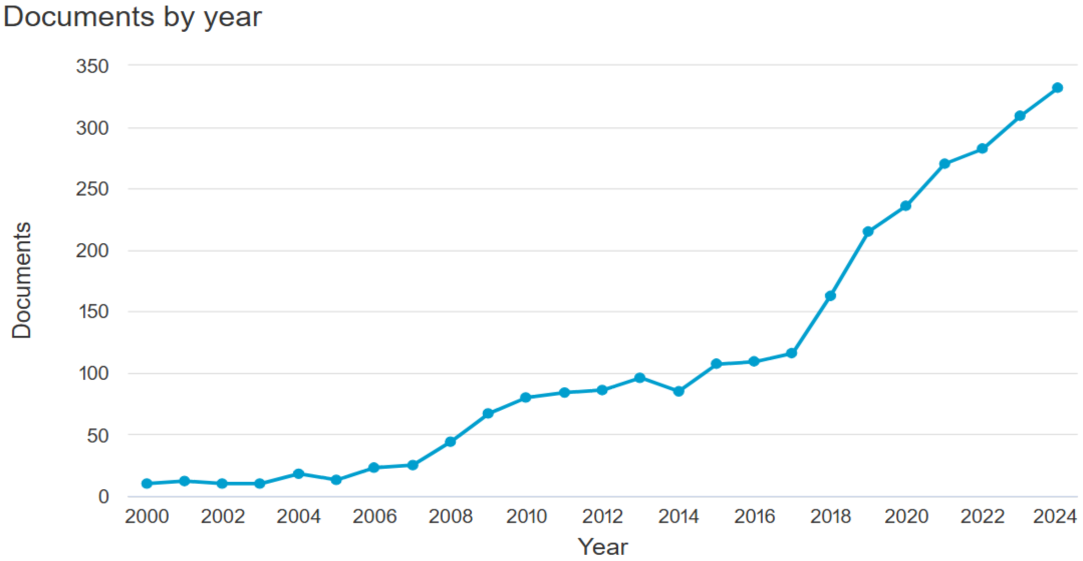

Figure 1. Increase of publication on groundwater, quality and analysis

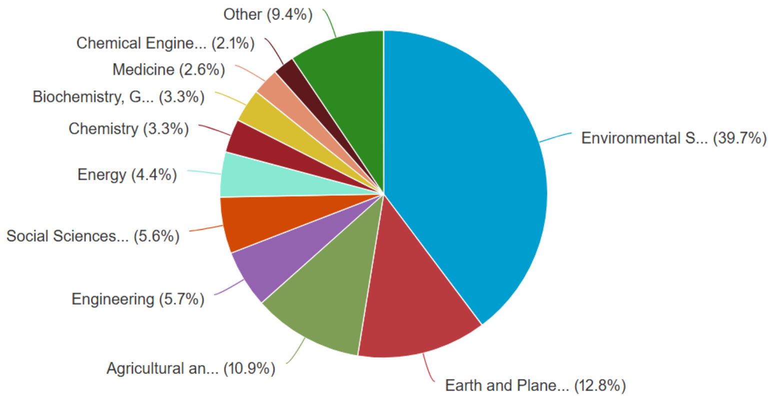

Figure 2. Distribution of production by area

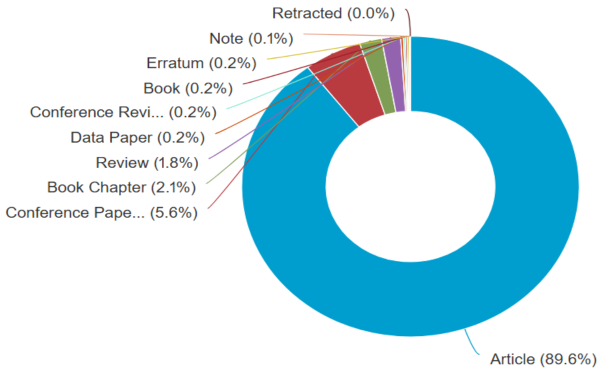

Figure 3. Nature of documents

In **Figure 4,** clusters can be identified through network visualization, along with the most prolific countries and inter-country collaborations, indicated by colored lines. The obtained histograms also indicate quantitatively the production by country (**Figure 4**).

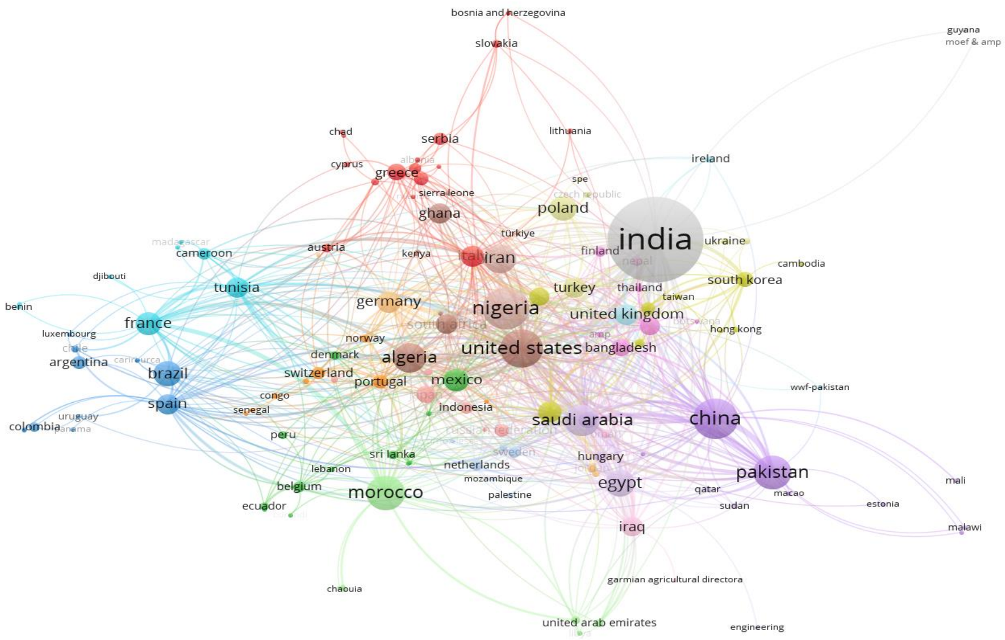

Figure 4. Network visualization of the Countries on VOS viewer

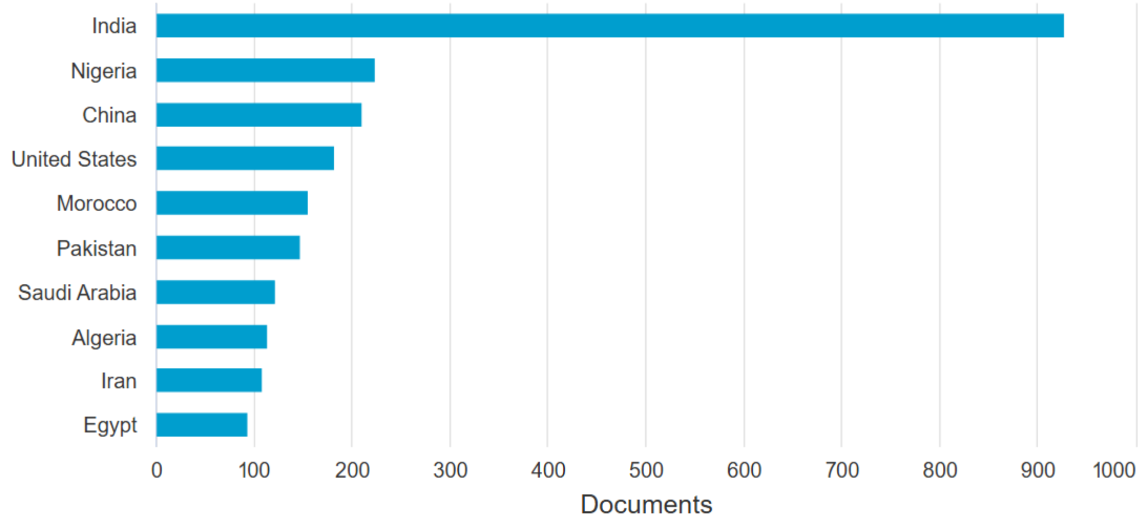

Figure 5. Histogram of the most Countries

Figure 6 shows an overlay visualization of the top-most active countries. The visualization depicts the publications of the top countries within a timeline from 2000 to 2024. India, with a dark purple node to indicate its concern around 2000, the other countries, colored yellow, have been publishing recently from 2000 to 2024.

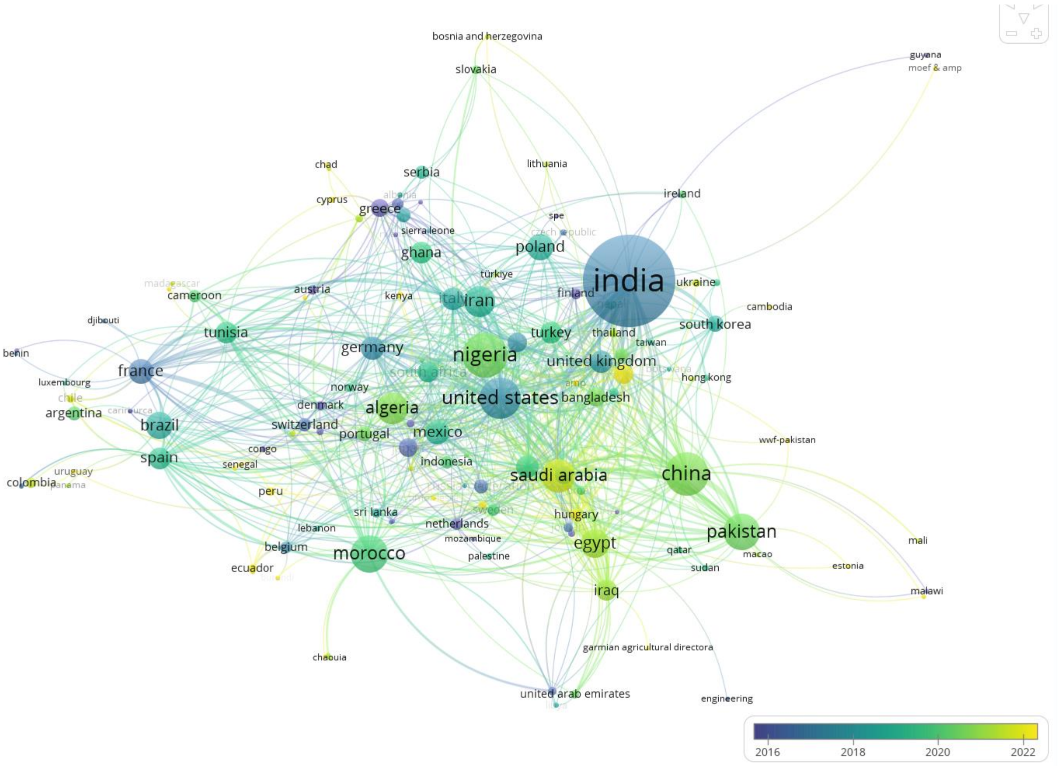

Figure 6. Overlay visualization of the Countries on the VOS viewer

The intensive exploitation of water resources, through pumping for irrigation purposes, as well as the water deficit observed in recent years, have led to the drying up of the large Tit Zill spring, which supplied drinking water to the village and all the douars of the rural commune of Almis Guigou. Currently, most of the population obtains its water from wells for irrigation and domestic consumption. This study, therefore, assesses the physicochemical quality of this water based on national and international standards relating to the potability of water intended for human consumption.

2. Methodology

2.1 Study area

The Guigou Plain, with a total area of 163 km², is an ancient intra-mountain valley carved at the contact of the North-Middle Atlas fault and drained by the Oued Guigou (**Figure 7**). It is located between 4°47' and 5°54' West longitude and between 33°15' and 33°27' North latitude. Situated in a semi-arid climate, it receives an average annual rainfall of 415 mm at the upper station of Aguelmame Sidi Ali and 347 mm at the lower station of Aït Khebbache for the period 1975-2024 (ABHS). The soils in the region, primarily composed of clay and silt, are rich in organic and mineral matter. These characteristics make the study area one of the most fertile and productive agricultural regions in the province of Boulemane (DPA, 2020).

The Guigou Plain is relatively poor in surface water, due to the high permeability of its substrate, attributable to the predominance of karst formations in the region (Bentayeb *et al.,* 1977). The Meso-Cenozoic lithostratigraphic series of the study area, spanning the Late Triassic to the Quaternary, consists of the following formations (**Figure 8**):

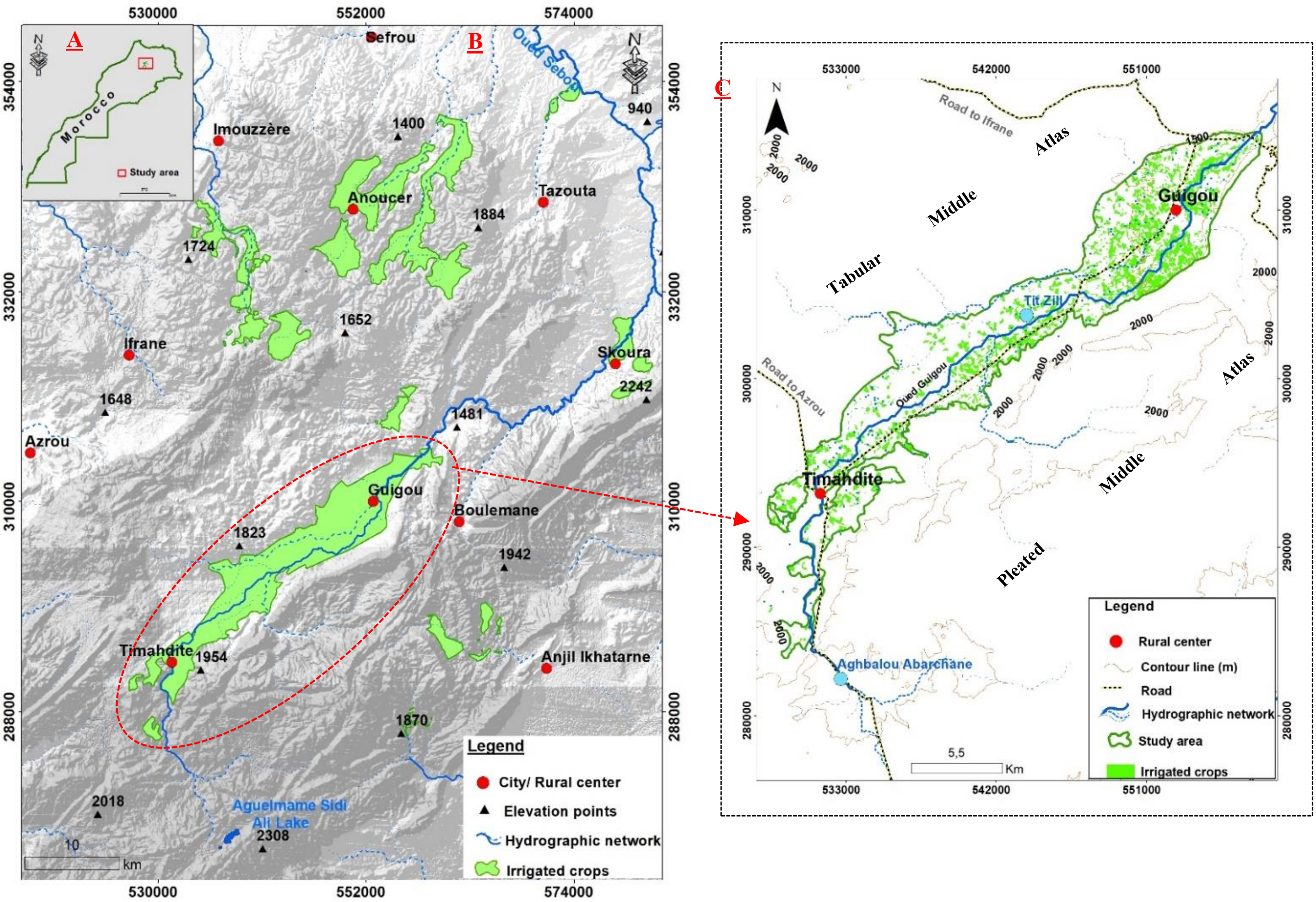

Figure 7. Geographical location of the study area. A) Location of the central Middle Atlas within Morocco. B) Position of the study area within the central Middle Atlas. C) Study area (the Timahdit-Guigou Plain).

• Upper Triassic - Lower Liassic: Red clay formations containing traces of evaporites, with the intercalation of a medial basaltic complex (Termier, 1936., Salvan, 1984., Fedan, 1988., Hinaje, 2004., Ouarhache *et al.,* 2012., Amrani, 2016). These formations are overlain by a Liassic carbonate sequence, which evolves from dolomitic to limestone facies (Colo, 1961., Michard, 1976., Martin, 1981, El Arabi, 1987, Fedan, 1988, Hinaje, 2004).

• Dogger: Succession of two main lithological units: the Boulemane marls and the Bajocian corniculated limestones (Michard, 1976, Fedan, 1988, Aït Slimane, 1989, Charroud, 1990, Akasbi *et al.,* 2001).

• Cretaceous: Alternating limestone and marl formations (Chbani, 1984., Charroud, 1990).

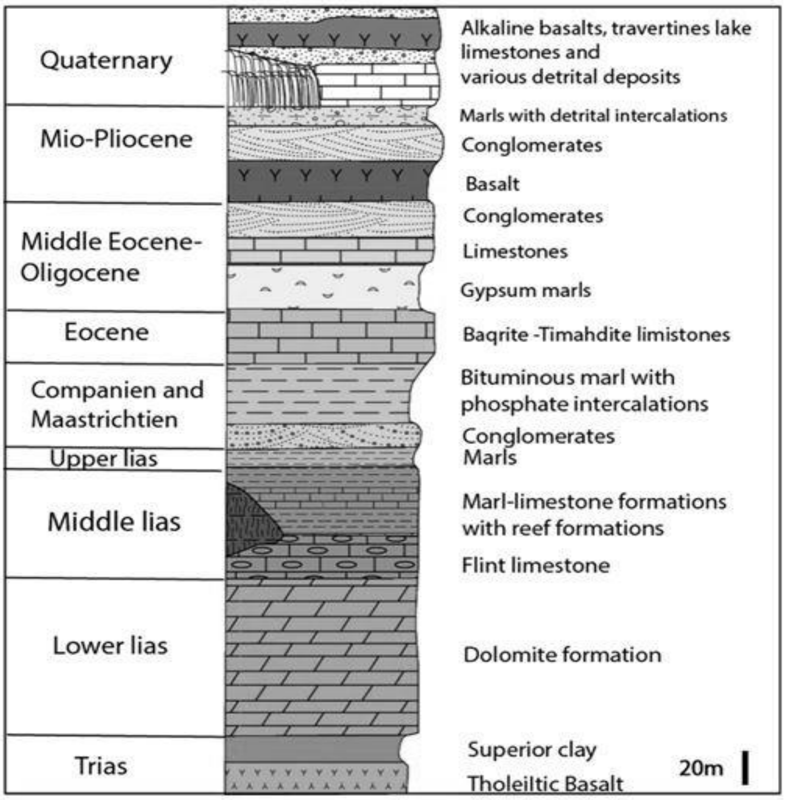

Figure 8. Synthetic stratigraphic log of the study area (in Amrani *et al*., 2022)

The results of a physicochemical measurement campaign of springs and wells conducted by Gamez in 1998 (Gamez *et al.,* 2000) in the study area revealed the existence of two main aquifers with different geochemical properties:

• The first aquifer, sulfated and chloride-rich, originates in the Permo-Triassic core of the Aïn Nokra syncline. It flows toward the Guigou Plain through a valley filled with colluvial deposits and through the alluvium of the Derdoura Oued.

• The second aquifer, with weak calci-magnesian mineralization, originates from the limestone and dolomitic Causse. A karstic circulation pattern can be proposed for this aquifer, flowing under basaltic cover to the paleo-valleys of the wadis draining the Causse. The Tit Zill springs constitute, at the base of the basalts and in the current bed of the Guigou, the emergence of these circulations.

2.2 Water sampling and Physico-chemical analyses

The analyses conducted in this study are based on groundwater samples taken from wells and springs used for irrigation and drinking water supply in the study area.
The sampling campaign was carried out during a high-water period. This period was chosen for three reasons. First, it occurred after the agricultural season. Second, it was performed after the first three months of rainfall, allowing the aquifer to recover from its water deficit and providing a better

understanding of the concentration of chemical elements from agricultural fertilizers remaining in the groundwater after each farming season. Third, it takes into account the lithological diversity of the area in order to cover the agricultural perimeter from the upstream Timahdit to the downstream Guigou. A total of eight samples were collected, six from wells and two from springs (**Figure 9**), in accordance with the recommendations of Rodier (2009). The physicochemical parameters measured in situ included temperature, pH, electrical conductivity, and dissolved oxygen.

2.3 Calculation of the Water Quality Index (WQI)

To assess water quality and suitability for consumption, the Water Quality Index (WQI) was calculated using the weighted arithmetic index method (Horton, 1965, Brown *et al.,* 1970; Benkaddour *et al.,* 2020; Talhaoui *et al.,* 2020; El khalki *et al.,* 2024). The human consumption standards suggested by WHO (2011, 2017) and the maximum allowable limits recommended by Morocco (Norme Marocaine, 1991) were taken into account for the estimation of the WQI (**Table 1**). The IQE was calculated by taking into account nine physicochemical parameters, namely: pH, dissolved oxygen, ammonium (NH_4^+), nitrates (NO_3^-), phosphates (PO_4^{3-}), total nitrogen and orthophosphates (PO_4^{3-}). In addition, two physical parameters were integrated into the analysis: temperature (°C) and electrical conductivity (µS/cm).

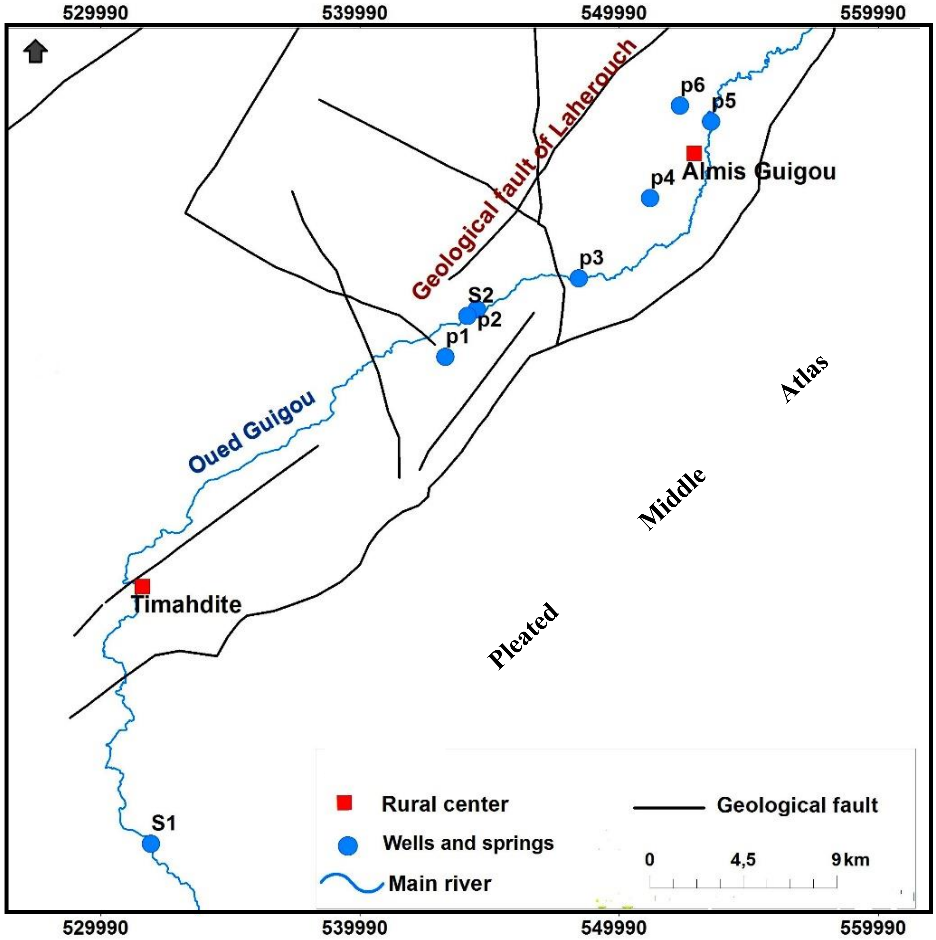

Figure 9. Location of groundwater sampling points in the study area

Table 1. Permissible limit values for physicochemical parameters according to Moroccan and WHO standards

Parameters	Unit	Maximum admissible value (MOROCCO)	Maximum allowable limits (WHO: 2011, 2017)
Temperature	°C	25°C	20
pH	---	6,5 - 9,5	6,5 - 8,5
Conductivity	µs/cm	2500	1500
Dissolved oxygen	mg/l	4	Unfixed value
Ammonium	mg/l	0,5	0,2
Nitrates	mg/l	50	50
Azote total	mg/l	10	Unfixed value
Orthophosphates	mg/l	0.5	0.4
Total phosphorus	mg/l	0,3	0,5

The Water Quality Index (WQI) was calculated in four steps:

1) Assigning parameter weights

Each physicochemical parameter was assigned a weight (wi) based on its importance in assessing water quality. Weights range from 1 to 5, depending on their impact on health and the environment.

2) Calculation of the relative weight (Wi)

The relative weight of each parameter is obtained using the following relationship:

$$\mathrm{Wi} = \frac{wi}{\sum wi} \qquad \textbf{Eqn. 1}$$

where:

- Wi is the relative weight of parameter i,
- wi is the weight assigned to the parameter,
- n is the total number of parameters.

3) Determining the quality score and calculating the WQI

The quality score (qi) for each parameter is determined by:

$$\mathrm{qi} = \left(\frac{\mathrm{Ci}}{\mathrm{Si}}\right) \times 100 \qquad \textbf{Eqn. 2}$$

where:

- Ci is the measured concentration of parameter i,
- Si is the potability standard according to WHO (2011, 2017) (Table 1).

The water quality index is then calculated by:

$$\mathrm{SIi} = \mathrm{Wi} \times \mathrm{qi} \qquad \textbf{Eqn. 3}$$

$$\mathrm{WQI} = \sum \mathrm{SIi} \qquad \textbf{Eqn. 4}$$

4) Water Classification and Use According to the WQI

The WQI obtained allows water to be classified into different categories, indicating its quality level and potential use:

Table 2. Classification of water quality and status based on weighted arithmetic WQI Method (Brown *et al.*, 1970)

Water quality index level	Water quality status
0-25	Excellent water quality
>25 - 50	Good water quality
>50 - 75	Poor water quality
>75 - 100	Very Poor water quality
> 100	Non-potable water

3. Results and Discussion

The groundwater of the Guigou plain is currently considered a major factor in economic and social stability, especially after the complete drying up of the wadis and the main Tit Zill spring, which supplied the population of the plain with drinking water. As a result, groundwater is an essential resource for drinking water and irrigation. It is therefore imperative, in this region, to study the physicochemical quality of borehole water and compare it with potability standards (WHO: 2011, 2017).

Groundwater quality parameters

The temperature, pH and dissolved oxygen values in the studied wells and springs do not show significant spatial variation. The temperature varies between 9 and 14°C, the pH between 6.3 and 7.4 and the dissolved oxygen concentration between 8.36 and 8.88 mg/L. On the other hand, the recorded conductivity shows a remarkable spatial variation (450 to 1428 µs/cm). Compared to Moroccan national and international drinking water standards, the values obtained remain generally in line with regulatory thresholds. However, the pH measured at stations S2 (Source Toghache) and P6 is below 6.5, reflecting marked acidity that exceeds the thresholds. These results diverge from those reported by Abboudi Akil *et al.,* (2014), who, based on sampling carried out in the same study area, highlighted a basic pH trend, with values between 7.73 and 8.89.

Table 3: Physicochemical data of groundwater

Stations	Temperature (°C)	pH	Conductivity (µs/cm)	Dissolved oxygen (mg/l)
S1	9	7,3	450	8,36
P1	12	7	1082	8,81
S2	12	6,3	765	8,62
P2	11	6,9	1428	8,75
P3	14	7,4	1161	8,69
P4	12	7,4	1194	8,66
P5	12	7,3	966	8,88
P6	10	6,4	1122	8,72

P: well; **S**: spring

Nitrates (NO_3^-), a major indicator of agricultural pollution, show concentrations ranging from 2.067 mg/L (Abarchane Spring, S1) to 15.835 mg/L (P4 station). Although these values show spatial variability, they remain well below the 50 mg/L threshold recommended by the World Health Organization (WHO: 2011, 2017) for drinking water. Total nitrogen, which mainly comes from anthropogenic activities in groundwater (OECD, 2018), exceeds national standards in all wells in the study area, with the exception of natural springs S1 and S2 (**Figure 10**).

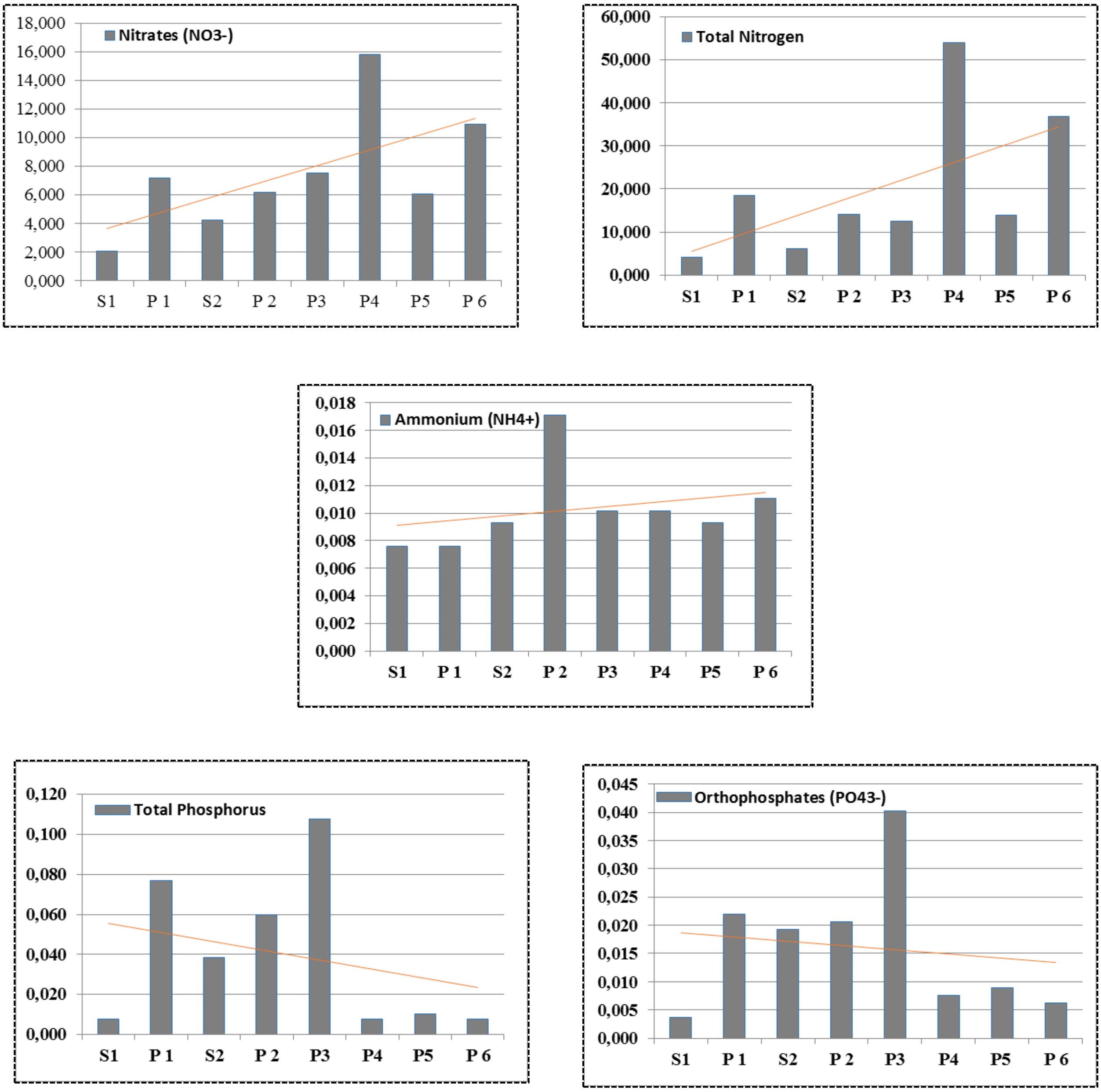

Figure 10. Contents and spatial variation of the physical and chemical parameters analyzed in the study area

These results demonstrate a significant impact of human activities, particularly agricultural and domestic, on groundwater quality. Artificial nitrogen fertilization is the main source of nitrogen, with the aim of compensating for the deficit and meeting the needs of market garden crops (potatoes and onions) in this plain (Lazhar, 2024). Stations P4 and P6 have much higher concentrations than the other two stations, indicating significant nitrogen pollution in these areas. Ammonium (NH_4^+) was detected at concentrations below 0.2 mg/L in all the stations studied, with the maximum concentration recorded at station P2. The concentrations of these three parameters follow an increasing gradient from upstream (Timahdit) to downstream (Guigou). This downstream increase can be explained by increased anthropogenic pressure resulting from higher population density, enhanced socio-economic dynamics and intensified agricultural practices (**Figure 10**).

The histograms of phosphorus compound concentrations indicate that the waters studied do not present a significant risk of pollution. The measured concentrations are generally low, even negligible. The minimum values were observed at the Abarchane spring (S1), with 0.004 mg/L of orthophosphates and 0.008 mg/L of total phosphorus, while the maximum values were recorded at station S3, with 0.04 mg/L and 0.1 mg/L respectively. This could be explained by the fact that orthophosphates are easily fixed by the soil (Rodier *et al.,* 1996).

Water Quality Index (WQI)

The assessment of groundwater quality intended for drinking water in the study area was carried out based on the Water Quality Index. This assessment is based on the maximum values of the standards recommended by the WHO (2011, 2017) as well as on the weightings assigned to the various physical and chemical parameters, based on their relative importance in overall water quality. The first table below presents the parameters considered and their respective weights. The second table lists the WQI values obtained for each sampling point and their classification according to water quality thresholds.

Table 4. Weightage (wi) and relative weightage (Wi) of each groundwater quality parameter

Parameter	wi	Wi
Temperature (°C)	1	0,043
Conductivity (µs/cm)	2	0,087
Ammonium (mg/l)	3	0,130
Nitrates (mg/l)	5	0,217
Total Nitrogen (mg/l)	4	0,174
Orthophosphates (mg/l)	4	0,174
Total Phosphorus (mg/l)	4	0,174

Table 5. Water quality index and its quality class for each in study area

Sampling points	WQI value	Water type
P1	48,38	Good water quality
P2	42,15	Good water quality
P3	41,04	Good water quality
P4	64,00	Poor water quality
P5	36,60	Good water quality
P6	53,70	Poor water quality
S1	13,58	Excellent water quality
S2	22,38	Excellent water quality

The analysis of the Water Quality Index (WQI) reveals a significant spatial variation in water quality in the study area. The natural springs (S1 and S2) have excellent quality, with respective indices of 13.58 and 22.38. In particular, the Abarchane spring (S1), located at the extreme upstream of the Guigou wadi valley, displays the best quality, and waters with low mineralization (Gamez *et al.,* 1999), the situation is explained by the rugged relief of the area, which limits agricultural expansion, as well as by the absence of habitats near the source.

The majority of the other sampling sites (P1, P2, P3 and P5) show generally good quality. However, some wells, notably P4 (64.00) and P6 (53.70), show indices indicating poor water quality, thus highlighting a potential alteration of the resource in these areas. This poor quality is reflected in high nitrogen concentrations. Analysis of the spatial distribution of sampling points in the study area indicates that agriculture is not the only factor contributing to the degradation of water quality. Indeed, the observed pollution is also affected by the discharge of domestic wastewater, as evidenced by the coincidence of the most polluted points with densely populated areas surrounding villages, devoid of sanitation networks, in agreement with those found by El Ouahidi (2017) in the groundwater table of the province of Safi (Morocco). However, although the quality of groundwater is generally good for supplying the population with drinking water after the drying up of the large Tit Zill spring, it should be noted that the waters of the Timhadit-Guigou aquifer are not immune to progressive contamination. The deterioration of water quality is noticeable in several places.

Conclusion

This study assessed the quality of groundwater in the Timhadit-Guigou aquifer intended for human consumption, using samples taken from wells and springs used for irrigation and drinking water. Analysis of the Water Quality Index (WQI) applied to groundwater in the study area reveals significant variability in water quality, resulting from both natural and anthropogenic factors. The results indicate that the majority of groundwater in the area chemically meets drinking water standards. However, the poor quality observed at two specific stations highlights localized pollution. Analysis of contamination parameters reveals excess nitrogen content at these two stations, suggesting a significant contribution from intensive agricultural practices, particularly the excessive use of nitrogen fertilizers, as well as untreated domestic wastewater discharge.

Therefore, given the vulnerability of the aquifer, due to the permeability of the substrate and increasing anthropogenic pressures in recent years (intensification of agriculture, population growth, etc.), it is crucial to implement continuous monitoring of water quality, accompanied by sustainable management strategies. This involves the installation of a sanitation network in the rural center of Guigou, which is home to a population of 12,913 inhabitants according to the last census (2024), as well as strict monitoring and control of the quantities of fertilizers and pesticides used in the region in order to preserve the Guigou aquifer, the only source of drinking water in this area.

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