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Effect of a hyperarid climate on groundwater salinity: A case study of the Ouargla shallow aquifer (Northern Sahara, Algeria)

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Abstract: Groundwater resources are typically affected by both global climate factors and anthropogenic activities. This influence is most apparent in arid and semi-arid climates of the Saharan desert. With rising temperatures and minimal precipitation, climate variability in these regions has a particularly significant and systemic impact on the chemical composition of shallow aquifer water. In this regard, our study aims to evaluate the climatic effects on groundwater in Saharan environments, using the Ouargla basin as a prime example. Water samples taken from 45 observation piezometers in our selected study area in February and June 2021 were used to assess the overall impact of inter-annual climate variations on salinity within this shallow groundwater basin. The obtained results show that groundwater located in the first three meters of shallow aquifer depth is directly influenced by surface climate. This pattern holds true for both observed seasonal periods. Stratification indices within the saturated zone were found to be positive, indicating an increase in groundwater salinity at lower depths and negative in shallower depths. This suggests a direct climate influence on this groundwater. These findings can be used to enhance sustainable development strategies in such environments, notably by quantifying salt accumulation and efficiently managing salinity exchange between saturated and vadose horizons.

Introduction

While groundwater is generally regarded as a 'drought-resistant' resource, most shallow aquifers are susceptible to annual or prolonged droughts (Hetzel et al. 2008). In many regions, aquifers serve as a vital source of freshwater, making groundwater quality crucial for the well-being of urban and agricultural areas that dependent on these water resources. Groundwater temperatures in shallow aquifers may increase in response to rising atmospheric temperatures, primarily due to heat conduction from the Earth's surface to the underlying groundwater system (York et al. 2002, Taylor and Stefan 2009). Elevated evapotranspiration can also lead to soil salinization, affecting both soil moisture quality and fertility, as well as the availability of water resources (Williams 1999).

The chemical composition of shallow groundwater in arid and hyper-arid regions is strongly influenced by a seasonal cycle of water evaporation, salt precipitation, and subsequent salt dissolution. In the summer, halite and gypsum salts precipitate due to the evaporation of upwelled water at ground surface level. During the winter or in cases of artificial groundwater recharge, the saline crust dissolves, followed by the percolation of this impaired water back into the groundwater system.

Due to the increasing influence of climate change and the associated rising temperatures, soil salinization has become a global ecological concern (Jianguo et al. 2014, Corwin 2020, Hassani et al. 2021). Over the past 150 years, average warming has increased worldwide, with a notable acceleration in the last 25 to 50 years. This trend is expected to continue in the future, further intensifying dependence on groundwater resources and exacerbating food security challenges (Folland et al. 2001). Hulme et al. (2001) observed that warming in the 20th century, especially during the last three decades, occurred at a rate of about 0.5ºC for the entire African continent. Predictions suggest that by 2080 and 2099, the annual average air temperature will be 3 - 4ºC higher compared to the 1980 - 1999 period (Christensen et al. 2007). Considering the interactions between shallow aquifera and the atmosphere, it is highly likely that groundwater quality degradation and soil salinization due to climatic stress will continue.

The Algerian Sahara is among the hottest and driest climate zones globally, covering an expansive area of over 2 million km². This vast desert stretches from the Atlas Mountains to the neighboring borders of Mali, Nigeria and Libya. The region is characterized by scant, irregular rainfall, ranging from 12 to 200 mm/year as one moves from north to south (Sekkoum et al. 2012). Temperatures are generally high, often exceeding 45°C, and are accompanied by very low relative humidity (Sekkoum et al. 2012). The Sahara is particularly vulnerable to climatic conditions that could have a detrimental impact on various socioeconomic sectors, including water resources. The extreme heat in this hyper-arid climate can significantly affect soil physical properties, such as soil texture and structure, which, in turn, can modify the chemistry of shallow groundwater. The concentration of total soluble salts also plays a crucial role in determining water quality for various sector uses.

Given these circumstances, this study aims to characterize the physico-chemical composition of shallow groundwater in order to assess geochemical variations associated with the climatic impact in the hyper-arid region of northeastern Algeria's Sahara.

Materials and Methods

Description of the Study Area

The Ouargla basin is a geologic depression with an extended surface area of approximately 750 km². It is located in the lower portion of the Quaternary *Oued* M'ya valley, a subbasin of the Lower Sahara. It is located 850 km away from Algeria's capitol city, Algiers (Fig. 1). This geologic depression has natural boundaries that are not all clearly defined. To the west, it is bounded by the Canntra and *Garet* El Bouib, a large Pliocene Calcareous-sandstone plateau with associated *Gours* or buttes (Aumassip et al. 1972). On the east, its boundary is less clear, as it is marked by a deeply eroded Mio-Pliocene red Sandstone plateau often buried beneath the desert sands of *Ergs* Touil, Bou Khezana, and Arifdji. To the south, the basin is bounded by sand dunes covering the ruins of the ancient city of Sedrata. Finally, to the north, the basin is limited by Zabret Bou Noura and a massive dune field that stretches along the left bank of the *Oued* N'sa to northernmost *Sebkha* Safioune (Djidel et al. 2008, Hadj Kouider et al. 2019). With an average valley slope gradient of <1‰, streamflow gradients in the area are very low, resulting in low hydraulic gradients within the underlying shallow groundwater system (ONA 2004, Idder et al. 2013).

The climate type is Hyper-arid desert (KÖPPEN classification *BWh*) having rare and irregular rainfall, with an annual average of 62.40 mm (Kharroubi et al. 2022). Diurnal and nocturnal temperatures are variable, with an annual mean temperature ranging from 4.8°C to 43°C in January and July, respectively (Medjani et al. 2021). Evapotranspiration rates are equally varied, ranging from 112 mm to 380 mm in the aforementioned months, as well (Chaouki et al. 2014).

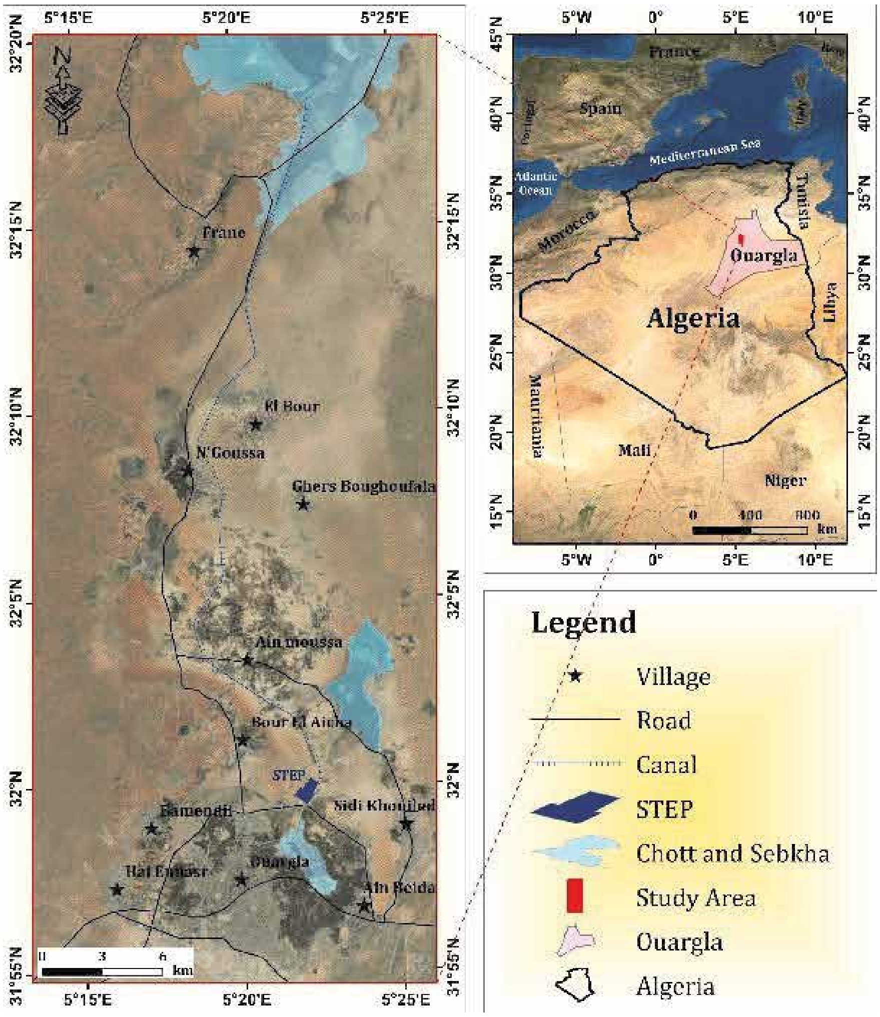

Figure 1. Location map of the Study area

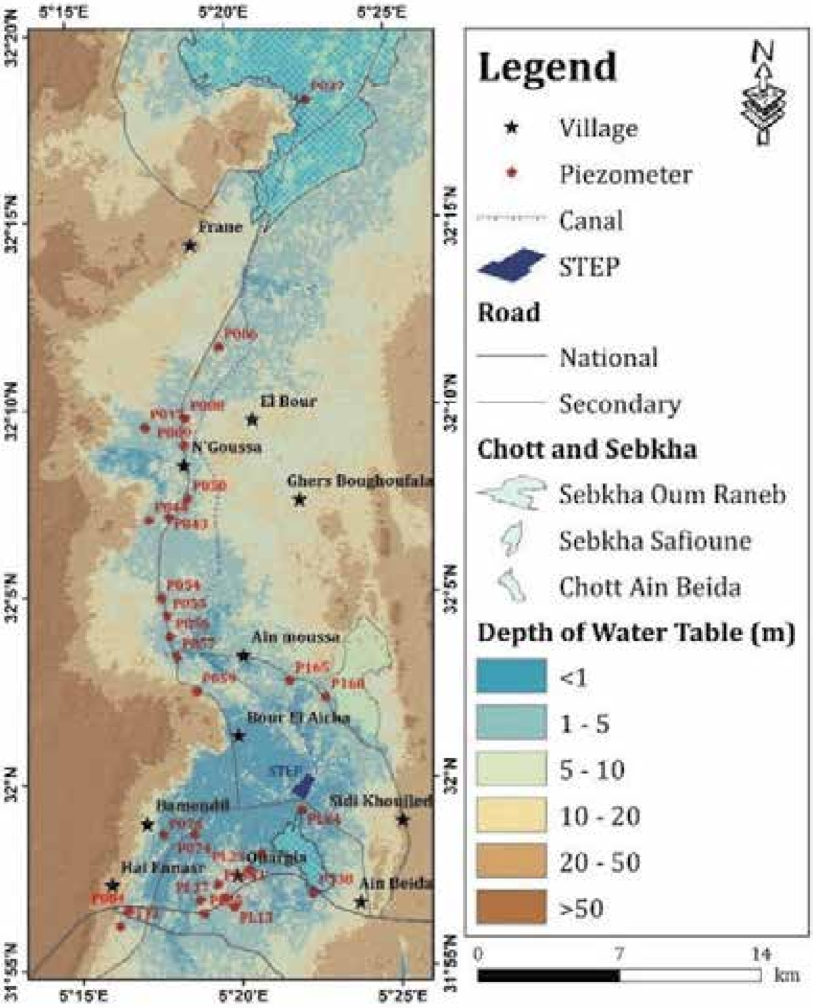

Figure 2. Sampling location map of the study area.

Precipitation events are considered negligible compared to dominant regional evaporation rates, which increase salinity in both soils and surface water bodies.

The Ouargla basin hosts a substantial unconfined phreatic aquifer situated above an impermeable clay layer at the base of the Ouargla valley. This clay layer effectively isolates it from two underlying deep fossil aquifers, namely the Terminal Complex, and the Albian/Intercalary Continental (Djidel et al. 2008). The basin's lithology is heterogenous, primarily comprised of fine to medium Quaternary aeolian quartzite sands. To the north and south of Ouargla, one finds alluvial clays interspersed with intermittent marls (Aumassip et al. 1972). Further north, gypsiferous sands and saline soils predominate, revealing the marked vulnerability of this natural environment to external anthropogenic and geogenic influences (Hamdi-Aïssa et al. 2004, Satouh et al. 2021). Socio-economic development in the region has necessitated the extraction of a significant quantity of water from boreholes, resulting in an escalating demand for daily water supply (Kharroubi et al. 2022, Slimani et al. 2023). Several wells have been drilled into the deep aquifers, especially within the Terminal Complex. Surplus water from domestic discharges and irrigation is often discharged directly into shallow aquifers, which adversely affects groundwater quality (Satouh et al. 2021). This groundwater is characterized by high salinity and has been classified as very hard (Belhadj and Boutoutaou 2017, Abba 2019).

In urban areas, static water table levels vary from 1 - 3 m, while in agricultural zones, they range from 0.5 to 0.9 m (Djidel et al. 2008). The water table can reach ground surface level, upwelling into ephemeral *Chotts* and *Sebkhas* within the Ouargla valley, and can extend to depths of up to 10 m in the bordering areas of Sandstone bedrock reliefs (Fig. 2).

Data Sources

Physiochemical parameters play an important role in water quality classification and assessment (Tank and Chandel 2010). Groundwater samples were collected at static groundwater table level during both high- and low-water periods in February and June 2021, respectively. A total of 45 samples were collected from piezometers (Fig. 2) distributed evenly across the study area, with 18 piezometers in February and 27 in June. Among the 27 samples collected in June, 14 were taken from two different groundwater levels: the first at the static water table and the second at the bottom of the piezometer.

Standard physical parameters, including pH, temperature, and electrical conductivity, were directly measured in the field (Table 1). Water level measurement were performed using standard manual piezometer probe. Hydrochemical analyses

Table 1 Statistical results of analyzed samples

Statistics	Water level	T°	pH	EC	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}
	m	°C		$mS.cm^{-1}$	$g.l^{-1}$						
February 2021											
Min	0.50	19.20	6.01	3.04	0.43	1.15	0.05	0.42	0.02	0.07	0.20
Max	10.50	23.20	7.80	174.49	186.66	31.70	1.09	110.33	10.56	21.39	1.12
Mean	2.58	21.73	7.09	40.69	32.77	8.21	0.30	21.38	1.32	2.58	0.60
STDEV	2.53	1.20	0.47	51.78	54.42	7.84	0.30	33.59	2.52	5.08	0.27
June 2021											
Min	0.50	25.00	6.38	3.76	1.18	0.55	0.14	0.51	0.02	0.09	0.21
Max	4.50	37.00	8.14	233.61	83.60	198.15	1.49	118.00	11.86	21.68	1.42
Mean	1.79	28.56	7.34	47.32	11.12	30.70	0.39	20.73	1.29	2.64	0.74
STDEV	1.11	2.76	0.37	61.49	16.24	51.45	0.36	33.91	2.37	4.42	0.32
Static level in June											
Min	0.50	25.10	6.38	4.72	0.96	1.23	0.14	0.80	0.05	0.13	0.26
Max	3.50	37.00	8.14	233.61	198.15	18.30	0.64	100.80	11.86	21.68	1.42
Mean	1.54	28.76	7.40	52.01	34.64	8.81	0.27	20.98	1.74	3.63	0.81
STDEV	0.84	3.32	0.43	63.04	55.60	5.50	0.16	31.02	3.04	5.74	0.35
Bottom level in June											
Min	2.50	25.50	6.49	4.82	0.92	1.25	0.12	0.75	0.05	0.13	0.29
Max	8.00	34.40	7.75	216.44	195.62	26.50	0.82	96.00	12.48	24.82	1.28
Mean	4.86	29.01	7.27	61.75	41.98	12.68	0.30	24.04	2.80	5.30	0.76
STDEV	1.97	3.06	0.33	57.25	54.29	7.56	0.20	28.06	3.60	6.64	0.35

of Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-} and HCO_3^- ions were carried out at the Geology of the Sahara Laboratory at Kasdi Merbah University, Algeria.

Methods

We first interpret the evolution of groundwater chemistry at the static water table level in order to determine the extent of the climatic effect in relation to the depth of the non-saturated zone. In other words, we aim to identify at what depth the groundwater in the unsaturated or vadose zone is still influenced by surface temperature during observation in both seasons. Secondly, we will characterize salinity evolution within the saturated zone by studying the variation of several chemical parameters between static water table level (H_1) and the bottom of various survey piezometers (H_2).

Stratification State

Water density stratification in relation to vertical temperature gradient is usually studied in lake waters to assess the climatic influence on these aquatic ecosystems. Several studies in the literature (Hutchinson 1957, Salençon and Thébault 1997, William and Lewis 1983) have proposed different classifications of lakes according to their stratification. The stratified state is evaluated by the vertical temperature gradient given by the formula (Eq. 1):

$$\Delta T/\Delta Z \tag{1}$$

where,

ΔT = difference between the water temperature at the lake surface (T_0) and the temperature measured at a given depth (T_1).

ΔZ = difference between the two measurement levels.

This same approach is used in this work, where the climatic effect on groundwater salinity is assessed by determining the vertical variation (or gradient direction) of physico-chemical elements between two measurement levels. This gradient is called the Stratification Index (**I_s**). In the case of conductivity, for example, the stratification index is given by the following (Eq. 2):

$$I_s = \frac{\Delta \mathrm{EC}}{\Delta \mathrm{H}} = \frac{EC_2 - EC_1}{H_2 - H_1} \tag{2}$$

where,

ΔEC = difference or change in conductivity.

ΔH = difference in groundwater depth in saturated zone.

Mineral Phases

In order to investigate the evolution of the equilibrium state of the mineral phases between both monitoring periods the USGS computer software program PHREEQC, version 3 was used to calculate the Saturation indices (**SI**) with the following formula (Eq. 3) (Parkhurst and Appelo 2013):

$$SI = \log(Kiap/Ksp) \tag{3}$$

where,

K_{iap} = ion activity product of the mineral

K_{sp} = solubility product of the mineral dissolution reaction

The degrees of groundwater saturation with respect to the solid mineral phase are as follows:

SI < 0 → Groundwater is *under-saturated*, favoring dissolution.

SI = 0 → Groundwater is at apparent chemical equilibrium or saturated.

SI > 0 → Groundwater is *supersaturated*, favoring precipitation.

Results and Discussions

Salinity at static water table level

Temperature effect vis-à-vis water level depth

Water temperature evolution, measured at the static water table level in different monitoring piezometers (Fig. 3), shows that

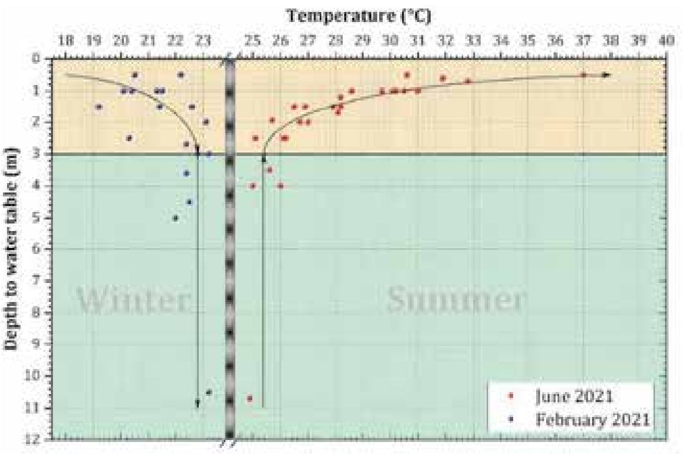

Figure 3. Water temperature evolution as a function of static water table level.

during summer season, temperature values increase as the water level approaches the surface. In contrast, during the winter season, water temperature rises along with the thickness of the unsaturated zone. This pattern extends to a depth of 3 m, and is directly related to the surface temperature effect, which reaches the depth mentioned earlier. Consequently, the influence of climate was observed to have little to no impact on shallow groundwaters greater than the 3-meter depth limit in either summer or winter. However, depths closer to the ground surface level showed a marked activity increase during both seasons, which is indicative of a direct climatic influence on these phreatic aquifer groundwaters. The direct influence of static level evolution within the vadose zone is evidenced by salt crystal precipitation and the formation of gypsum/calcite crusts due to high surface temperatures.

Conductivity Behaviour

Shallow groundwater salinity exhibited a noticeable change during the summer, as indicated by an increase in conductivity at depths close to and at ground surface level, with a maximum reading of 240 mS.cm^{-1}. Under the direct influence of high surface temperatures and negative water balance, concentrations of cations and anions increase causing shallow groundwater to become supersaturated with dissolved minerals. Over time, this leads to salt crystal precipitation and the formation of evaporite minerals, given favorable hydrological conditions. As a result, continuous salt crust accumulation and thickening are observed in the Ouargla basin (Fig. 4a).

Two anomalies to this overall observed behavior were noted. The first anomaly was observed in proximity to Palm groves at *Chott* Aïn Beïda, at a depth of 1 meter from the ground surface. Groundwater dilution had taken place at that site, brought about by surplus water infiltration from irrigation. The second anomaly was found at a depth of 4 m below the ground surface, where *Sebkha* evaporite lithology predominated over any anthropic influence.

pH Behavior

The evolution of pH as a function of static groundwater depth is classified in Fig. 4b. The dominant pH values, which were measured near or at pH neutral, characterized the majority of groundwater in the Ouargla basin. However, two distinct environments were observed for other pH values: (i) Acidic pH groundwaters were associated with *Sebkhas* characterized by high salt concentrations. (ii) Basic or alkaline pH groundwaters were found in *Chotts* and drainage areas receiving surplus water from palm irrigation.

Anion and Oxyanion Behavior

Chloride $[Cl^-]$ ions exhibited behavior similiar to conductivity (Fig. 5a). This observation suggests that shallow aquifer groundwaters have a hydrochemical chloride facies aspect (Nezli et al. 2007), especially considering their high solubility with increasing temperature. Sulfate $[SO_4^{2-}]$ ions showed anomalies near the ground surface during both winter and summer (Fig. 5b). The more accentuated anomaly in summer was notably associated with *Sebkhas* characterized by elevated salinity rates. These rates were found to be altered by the influx of irrigation water containing high SO_4^{2-} ion concentrations pumped from deep groundwater aquifers. Bicarbonate $[HCO_3^-]$ ions had significantly lower concentrations compared to others, particularly in groundwater close to the surface. This suggests that precipitated carbonate minerals are less soluble compared to other mineral salts. However, HCO_3^- concentrations showed a maximum increase, reaching 1.4 g.l^{-1} between depths of 4 and 7 m (Fig. 8). This could be evidence of the direct influence of near-neutral pH (Fig. 5c), causing a progressive chemical equilibrium shift towards CO_2 diffusion, which, in turn, promotes an increase in HCO_3^- ion concentration (Huang et al. 2021). Beyond a groundwater depth of 7 m, HCO_3^- concentrations decreased due to carbonates having reached chemical equilibrium. This decrease in HCO_3^- ion was measured in the deepest parts of the basin (>10 m), where groundwater possessed fewer charged ions. This finding confirms that there is no significant surface temperature effect on static groundwater depth beyond 3 m within this shallow aquifer.

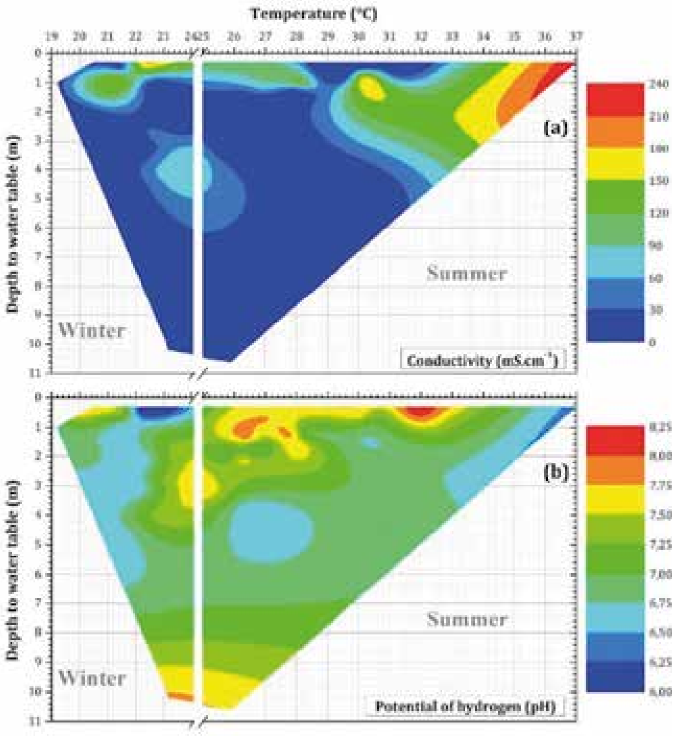

Figure 4. Conductivity and pH evolution as a function of water temperature and groundwater level depth.

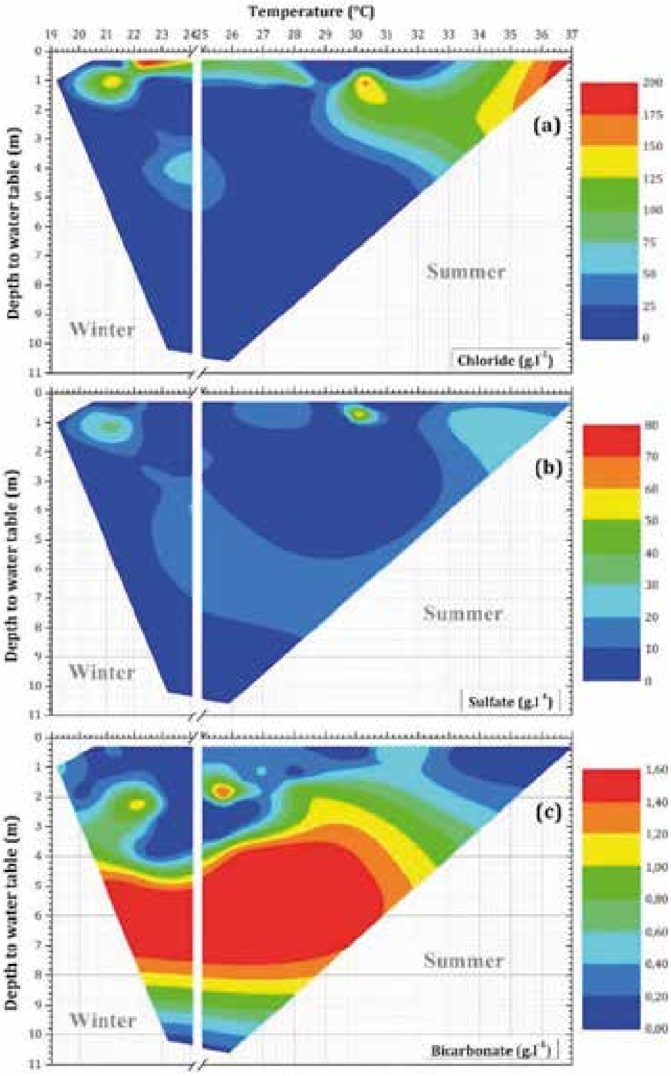

Figure 5. Anion and oxyanion evolution as a function of water temperature and groundwater level depth.

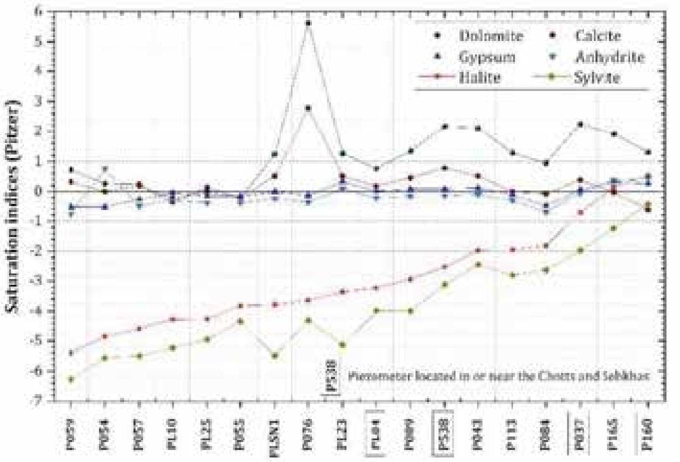

Figure 6. Saturation Index (SI) evolution as a function of groundwater depth.

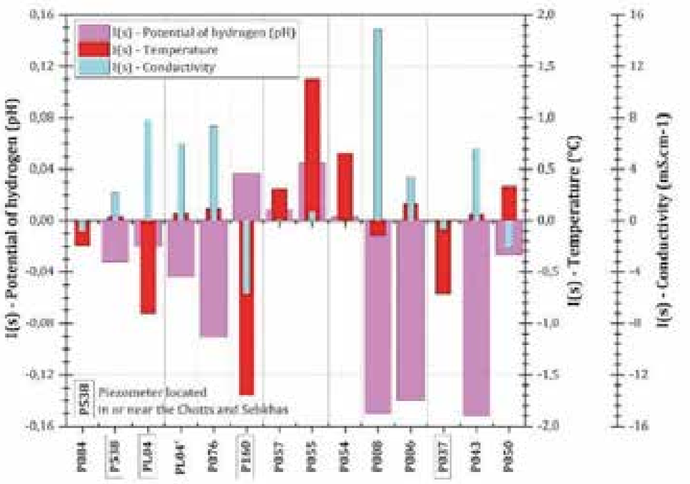

Figure 7. Stratification Index (Is) of selected physico-chemical parameters

Saturation Index Behavior

Calculated SIs show that the phreatic groundwater of the Ouargla basin is oversaturated (Fig. 6). The dissolution–precipitation sequence is governed by the ion activity and solubility products of each mineral. Carbonate minerals, such as Calcite ($CaCO_3$) and Dolomite [$CaMg(CO_3)_2$]], which have low solubility in fresh water at 0.0015 and 0.0032 g.l^{-1}**,** are consistently oversaturated throughout most of the basin (Klimchouk 1996, Patnaik 2003, Speight 2005). Sulfate salts like Anhydrite ($CaSO_4$) and Gypsum ($CaSO_4{\cdot}2H_2O$), which are relatively more soluble than carbonates at 2.00 and 2.53 g.l^{-1} (Klimchouk 1996, Patnaik 2003, Speight 2005), are generally in a state of chemical equilibrium or saturated. In contrast, chloride salts, including Sylvite (KCl) and Halite (NaCl), which are highly soluble (340 and 360 g.l^{-1}) (Klimchouk 1996, Speight 2005, Haynes 2016), are undersaturated, except in *Sebkha* Oum Raneb, where groundwaters are supersaturated due to NaCl precipitation.

Our study identified two anomalies. The first was found at a level where groundwaters were less saturated, showing carbonates and sulfate salts at chemical equilibrium. This anomaly was a direct result of continuous groundwater dilution by irrigation water. The second anomaly was found at *Sebkha* Oum Raneb, characterized by significantly higher SI, indicating supersaturation of NaCl and an undersaturation of $CaCO_3$. This anomaly is explained by a Ca^{2+} ion concentration decrease due to $CaSO_4{\cdot}2H_2O$ and $CaSO_4$ precipitation.

Saturated Zone Salinity Evolution as a function of Groundwater Depth

Stratification Index of Selected Physico-Chemical Parameters

The pH gradient exhibited two distinct trends: a decrease in pH and an increase pH with depth, which can be attributed to wastewater contamination or non-contaminated water infiltration, respectively (Fig. 7). Temperature and conductivity both showed decreasing trends associated with intense evaporation during *Sebkha* formation, and increasing trends by groundwater dilution from infiltration zones. Overall, the behaviors of temperature and conductivity were mixed.

Anion and oxyanion gradients also showed two distinct trends (Fig. 8a), one being associated with HCO_3^- ions, while the other was linked to chloride and sulfate evaporites. HCO_3^- ions exhibited a positive gradient (SI) in zones where the

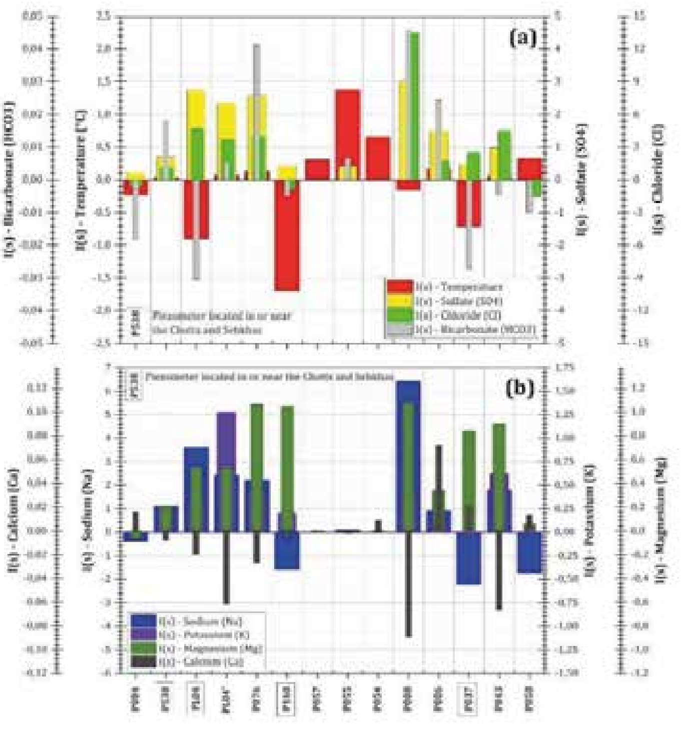

Figure 8. Stratification Index (Is) of Ions [a = Anions and Oxyanions; b = Cations]

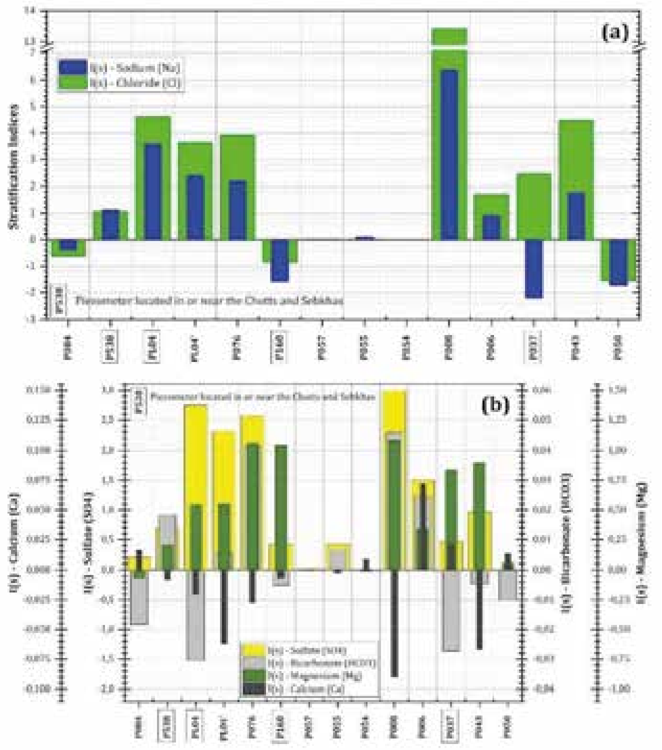

Figure 9. Stratification Indices [a = (Is) of NaCl; b = (Is) of Ca^{2+}-Mg^{2+}-SO_4^{2-}-HCO_3^-]

static groundwater level was far from ground surface due to stratification without external influences. On the other hand, a negative gradient was observed with *Chotts* and *Sebkhas*, which were directly influenced by surface temperature, leading to an increase in concentration until reaching carbonate saturation.

Cl^- and SO_4^{2-} ions showed similar positive trends throughout most of the study area. However, their behavior shifted to a negative trend near *Chotts* and *Sebkhas* due to $CaSO_4 \cdot 2H_2O$ precipitation, while NaCl remained undersaturated (Fig. 6). In contrast, the major cation stratification showed two distinct trends, one linked to alkali metals and the other alkali earth metals (Fig. 8b).

Alkali metal cations (Na^+, K^+) exhibited positive trends at locations far from ground surface across most of the basin. However, their behavior shifted to negative trends near *Chotts* and *Sebkhas*, with the exception of *Sebkha* Oum Raneb, which was due to NaCl supersaturation KCl undersaturation (Fig. 6).

Alkaline earth metal cations (Mg^{2+}, Ca^{2+}) showed a habitual, inversly proportional behavior to the aforementioned alkali metals. Trends were positive for Mg^{2+} ion but negative for Ca^{2+} ions, attributed to the low $CaCO_3$ solubility. These inverse trends were observed near *Chotts* and *Sebkhas* due to wastewater accumulation.

Stratification Index of NaCl

NaCl gradient showed two similar, yet distinct behaviors. One was positive, indicating its stratification throughout most of the basin. The other was negative due to stagnant waters under direct influence of surface temperatures (Fig. 9a). *Sebkha* Safioune (P037) showed an opposite trend, with a decrease in Na^+ ion, suggesting geogenic cation exchange with clayey sedimentary rock layers without anthropogenic interference.

Stratification Index of Ca^+ and Mg^{2+} in relation to HCO_3^- and SO_4^{2-}

In general, the behavior of SO_4^{2-} ions exhibited similarities with that of Mg^{2+} ions. However, HCO_3^- and Ca^{2+} ions displayed distinct behaviors (Fig. 10) due to the differences in solubility between calcium evaporites, such as CaCO3, and those containing magnesium, like $[CaMg(CO_3)_2]$ or Blœdite $[Na_2Mg(SO_4)_2 \cdot 4H_2O]$]. There was also strong competition for available Ca^{2+} ions, given their presence in both carbonates and gypsum ($CaSO_4 \cdot 2H_2O$).

Spatio-Temporal Behaviour of Saturation Index

The SI behavior trends (Fig. 10) indicate that both $CaCO_3$ and $CaSO_4 \cdot 2H_2O$ show somewhat positive and somewhat negative changes compared to the aforementioned I_s case. On the other hand, NaCl experienced an increase in SI with increasing depth, attributed to groundwater dilution from irrigation discharge.

Previous research conducted in arid climates (Taupin et al. 1990, Woods 1990, Yang et al. 2021, El Fergougui et al. 2016,) suggests that the climatic impact on shallow aquifer groundwater typically follows a two-zone pattern based on evaporation rate. Firstly, when the water table is close to the surface, the climatic effect is at its peak due to high evaporation rate. Secondly, as the water table recedes from the surface, this effect diminishes. According to Tesco (1986), a significant portion of groundwater salinity in the Ouargla shallow aquifer is attributed to the climatic effect. The shallow water level in this aquifer results in the highest levels of evaporation, thus contributing to observed high salinity. Estimations of evaporation within the same aquifer by El Fergougui et al. (2016) indicate that it reaches its maximum value, equaling potential evaporation, when the water table is situated between

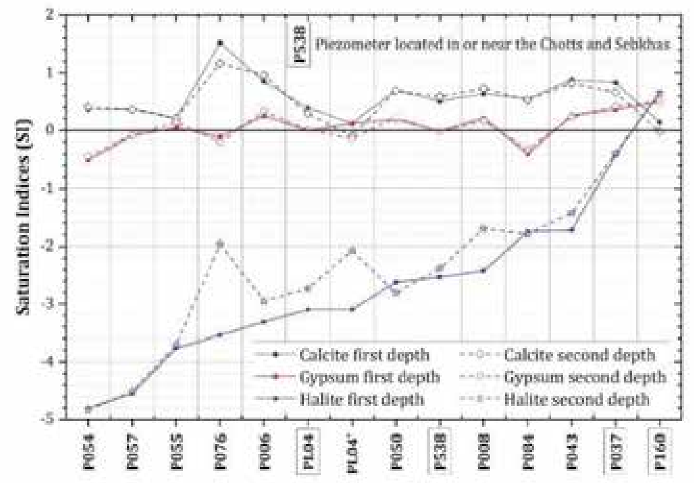

Figure 10. Evolution of saturation indices (SI) within the saturated zone.

0 and 60 cm from the surface. Typically, this horizon is utilized for cultivating crops (Semar et al. 2019). This raises concerns about salinity monitoring in this aquifer to ensure the quality control of irrigation water, measure the soluble salts accumulation in the soil's root zone, and establish water and salt balances for water table.

Conclusion and Recommendations

The shallow groundwater in the Ouargla basin is unsuitable for use due to its poor quality and permanent degradation. These shallow waters, aggravated by the rise in the static level of the water table, have had devastating effects on agricultural soils.

Our study revealed that surface temperatures had a direct effect on shallow aquifer groundwater from ground level to 3 m in depth. The behavior of salinity, in relation to the thickness of the vadose zone, showed that temperature had a very strong influence on drainage areas receiving stagnant waters in *Chotts* and *Sebkhas*, thus altering natural geogenic processes. This anthropic influence produced a shallow groundwater salinity decrease in terms of static depth levels.

The salinity behavior concerning water table depth in the saturated zone showed a positive Stratification Index, with a groundwater salinity increase observed at lower depths far from climatic influence. In contrast, negative indices were observed at shallower depths, indicating a direct climatic influence on these groundwaters.

Considering the critical situation characterizing the Ouargla endorheic basin, we recommend adopting adaptive solutions aimed at lowering the static water table to a depth of 3 m. This lowering of the water table would help reduce the spread of local salinity and prevent groundwater upwelling, which has adverse effects on adjacent agricultural soils. Furthermore, it is essential to ensure efficient control of both the quality and quantity of water utilized for irrigation, along with seasonal estimations of evaporation at various water table depths, and the subsequent salt deposition. Implementing proper water resource management, improving drainage system networks, wastewater treatment, desalination, traditional hydrologic knowledge (*e. g.*, *Foggaras*), educational initiatives to raise public awareness about water conservation, sustainable pumping practices, and in-depth groundwater studies are all viable solutions to prevent land degradation, desertification and ultimately protect the precious groundwater resources of the Ouargla basin for future generations.

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