Hydrogeochemical and Environmental Assessment of Groundwater and Soil Salinization: Implications for Agricultural Sustainability in the Oued Righ Valley, Lower Algerian Sahara

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Abstract

In the hyper-arid Oued Righ valley, in the Lower Algerian Sahara, the Terminal Complex (TC) aquifer is a main source of water for irrigation, industry and drinking. We analyzed groundwater from this aquifer, together with soil samples from 151 sites in the valley, to find out what controls the mineralization of the water and how it relates to the salt that accumulates in the soils. The water is neutral (pH 7.10–7.53) but heavily mineralized, with TDS averaging 2395 mg/L and electrical conductivity 4796 µS/cm. Chloride (mean 1008 mg/L) and sulfate (1431 mg/L) exceed 250 mg/L in every sample, and calcium and magnesium are also high. The correlation between calcium and sulfate (r = 0.62) and the low bicarbonate content point to the dissolution of gypsum and anhydrite, although a mean Ca/SO_4 molar ratio of about 0.7 indicates that this cannot be the only process. Nitrate and phosphate are low, yet nitrite reaches 10 mg/L, fluoride 2.2 mg/L, and iron exceeds 0.3 mg/L in some samples. The water should therefore not be drunk untreated, and its high salinity makes irrigationdependent on leaching and drainage. The soils are weakly alkaline (pH mostly 7.4–7.8) and extremely saline, with electrical conductivity of the soil solution up to 146 dS/m. Sodium and chloride vary almost in step (r = 0.985), and the EDX spectrum of the evaporation residue is dominated by chlorine and sodium (atomic Na/Cl 0.67), consistent with sodium chloride as the main salt.

Keywords: Terminal Complex aquifer; groundwater hydrochemistry; gypsum and anhydrite dissolution; soil salinization Agricultural; Sustainability; kriging; fluoride; arid zone; Oued Righ.

1. Introduction

Salinity is a constraint on irrigated agriculture in the Oued Righ Valley, where low rainfall limits natural leaching and high evaporative demand favors salt accumulation. Irrigation in the valley relies heavily on groundwater pumped from deep boreholes. Part of the surplus irrigation water drains into the valley's main channel, which also receives wastewater (Moulla and Guendouz, 2003). Intensive use of the deep aquifers has been linked to a rise in the shallow water table (Hammadi et al.,2022). Where drainage is inadequate and the water table lies close to the surface, upward movement of saline water and subsequent evaporation can lead to salt accumulation in the root zone and near the soil surface (Koull et al., 2013).

The Terminal Complex (TC) is one of the deep aquifer systems tapped in the valley. Studies from the northern Sahara have reported saline groundwater and identified evaporite dissolution as one process that contributes to mineralization (Slimani et al., 2017; Khebizi et al., 2020). In the Souf, Taibet, and other parts of the eastern Algerian Sahara, some measured constituents have exceeded drinking-water guideline values (Tabouche and Achour, 2010; Zaiz et al., 2017; Bettahar and Sener, 2024; Bettahar et al., 2026). In the Oued Righ Valley itself, Hammadi et al. (2022) reported electrical conductivities of 2–9 dS/m in TC groundwater and identified a predominantly sodium–sulfate facies in the second aquifer unit.

Koull et al. (2013) examined irrigation-water quality and soil salinization in the valley and reported a calcium–sulfate facies in the soils they studied. These local studies provide a basis for interpreting both groundwater chemistry and soil salinity. The present study examines the major-ion chemistry of TC groundwater alongside the ionic composition and electrical conductivity of soil extracts. It also uses energy-dispersive X-ray spectroscopy (EDX) to characterize the elemental composition of the residue obtained by evaporating a soil extract. The groundwater and soil results are interpreted at the valley scale.

The study had three objectives. The first was to compare selected groundwater constituents with drinking-water guideline values and acceptability criteria. The second was to examine which mineralization processes were consistent with the observed relationships among major ions. The third was to describe the ionic composition of the soil extracts, assess how their electrical conductivity varied across the sampled sites, and characterize the elemental composition of the evaporation residue.

2. Study area

2.1 Location and climate

The Lower Sahara is known for its sand dunes, salt flats and artesian waters (Halassa et al., 2018). It is bounded to the north by the Saharan Atlas, to the east by the Tunisian–Libyan Dahar escarpment, to the west by the M'Zab ridge, and to the south by the Tademaït and Tinghert highlands (Benkhedda et al.,2026) (Fig. 1). The Oued Righ lies within this region as a linear depression running north to south for about 125 km, lined with palm groves. From south (upstream) to north (downstream), the main oases are El-Goug, Blidet-Amor, Tamellaht, Temacine, Touggourt, Moggar, Tamerna, Djamaa, Ourlanha, M'Ghaier, Ourir and Oum El-Thiour.

The climate is hyper-arid Saharan climate, winters moderated, and of a permanent drought; precipitation hardly exceeds 45 mm / year, with average maximum temperatures 43 ° C and the office plurality of annual evaporation exceeds almost 60 times that of pluviometry (2759mm/year) (Laouini et al.,2019). The available water reserve is exhausted throughout the year, which leaves an annual agricultural water deficit, and groundwater is the only water resource of the valley. The Oued Righ, the most abundant watercourse of the Lower Algerian Sahara, is itself an entirely artificial river fed by the seepage of wastewater from the oases and settlements (Moulla and Guendouz, 2003). Boreholes supply irrigation, industry and domestic use.

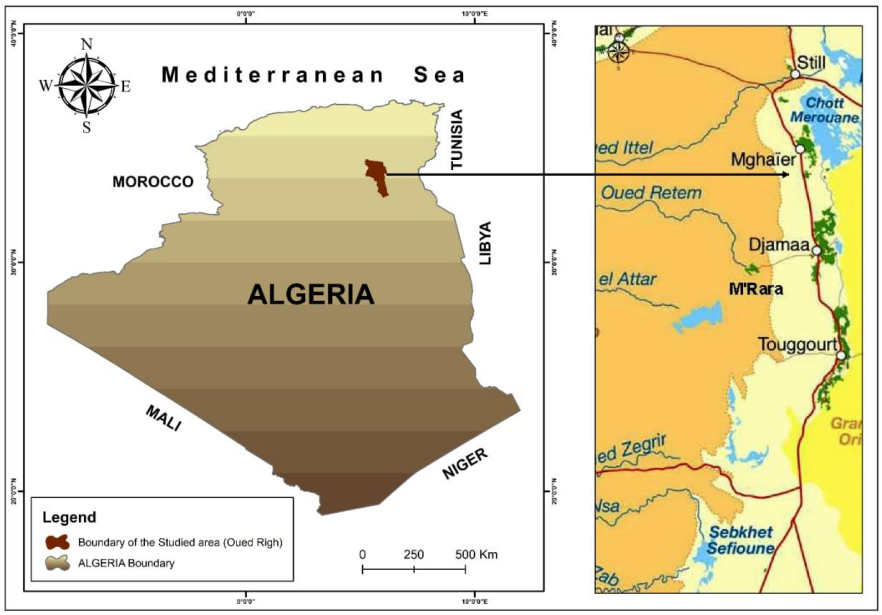


Fig. 1. Geographical location of the study area. (in Oued Righ valley).

2.2 Geology and hydrogeology

The Terminal Complex (TC) aquifer covers about 350,000 km² (Slimani et al., 2017). Its extent, piezometric levels and flow directions are shown in Fig. 2. In the Oued Righ it is a relatively shallow system with low water temperature (Chaib et al., 2013; Bettahar and Sener, 2024; Bettahar et al., 2026), and its chemical quality is good at the edges of the basin and average at its center.

It consists of three more or less independent artesian water tables (Habes et al., 2016). The first is about 20 m thick and lies at depths of 40 to 100 m, depending on the area. The second is about 30 m thick and lies at 100 m or deeper. The third is a limestone water table, not yet exploited in all areas, which is generally reached at 150 to 200 m. Taken together, the water tables lie between about 40 and 400 m depth.

The waters circulate through formations of clay, gypsum and anhydrite (Bel and Demargne, 1966). The hydrogeochemistry of the area is controlled mainly by water–rock interaction and by cation exchange (Cornet, 1964), and the contact of the confined waters with these geological formations is the probable origin of their mineralization (Fabre, 1976).

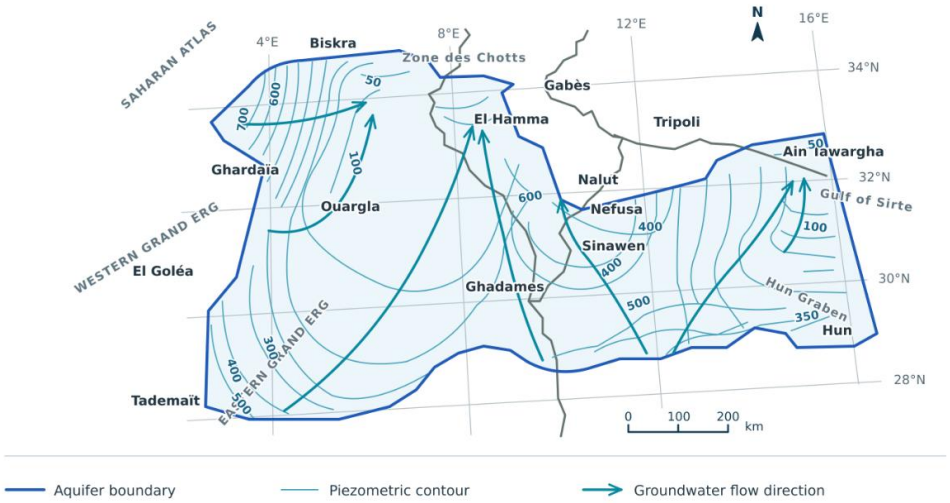


Fig. 2. Limits of the TC aquifer, with piezometric levels and flow directions (Baba Sy et al., 2006; redrawn by Z. Chini, 2012).

3. Materials and methods

3.1 Sampling

Groundwater samples were collected from the Terminal Complex aquifer along the Oued Righ valley, and soil samples at 151 sites across the same region (Fig. 1). The two sets were characterized within the valley, and no individual borehole was linked to a particular sampled plot.

3.2 Groundwater analysis

Electrical conductivity (EC) and pH were measured on site with digital instruments. The other constituents were determined in the laboratory following the standard methods of the American Public Health Association. Calcium, magnesium, bicarbonate, carbonate, chloride and TDS were analyzed by volumetric titration: Ca^{2+} and Mg^{2+} with EDTA (0.05 N), HCO_3^- and CO_3^{2-} with sulfuric acid, and Cl^- with silver nitrate (1 N). Sodium, potassium and sulfate were measured by flame photometry. Nitrate, fluoride and silica were determined by UV–Vis spectrophotometry.

3.3 Soil solution

The soil solution, meaning the water held in the soil, was analyzed for pH, EC and the major ions. EC was measured directly, which gives a quick and reliable estimate of the total salt content of the solution (Venkatramanan et al., 2016). The cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-) are expressed in meq/L, and EC in mmhos/cm.

3.4 Salt extraction and EDX analysis

To identify the salts that accumulate in the soil, 100 g of salt-affected soil was placed in a beaker and covered with distilled water. The mixture was stirred gently with a magnetic stirrer so that the salts dissolved, then poured through a filter. The sand stayed on the filter, and the salt solution was collected in a clean container. The container was placed in an oven at 105 °C until all the water had evaporated and salt crystals formed, and the crystals were dried to remove any remaining moisture and limit contamination (Fig. 3).

The salt was then analyzed by energy-dispersive X-ray spectroscopy (EDX), which gives the elemental composition of a solid sample.



Fig. 3. *Salt-affected soil sample and salt residue obtained after extraction and evaporation.*

3.5 Statistics analyses

For each parameter we computed the mean, standard deviation, minimum, maximum, variance and, for the soil solution, the coefficient of variation. Relationships among parameters were explored with simple correlation coefficients, among the physico-chemical parameters of the water and between the cations and anions of the soil solution.

Maps of soil pH, EC, cations and anions were produced by kriging, a geostatistical interpolation method (Kumar et al., 2007; Montero et al., 2015; Seyedmohammadi et al., 2016).

4. Results and discussion

4.1 Water quality against guideline values

Table 1 gives the statistics for the Terminal Complex groundwater and the reference value against which each parameter was compared.

Table 1. Descriptive statistics of the Terminal Complex groundwater in the Oued Righ valley and reference values (WHO; Zaiz et al., 2017; Saber, 2021).

Parameter	Reference value	Mean	SD	Min	Max
pH	6.5–8.5	7.33	0.14	7.10	7.53
Redox potential (mV)	–	−7.93	8.47	−20.90	1.50
EC (µS/cm)	500–1500	4796.25	1175.39	2210	5830
Temperature (°C)	12–30	23.38	5.25	18.90	30.10
TDS (mg/L)	≤ 1000	2395.25	771.18	1112	3080
Salinity (g/L)	–	2.60	0.68	1.10	3.20
Free CO_2 (mg/L)	≤ 10	32.42	28.58	13.89	101.89
Ca^{2+} (mg/L)	≤ 100	422.84	80.07	240.48	521.04
Mg^{2+} (mg/L)	≤ 50	227.55	55.95	109.37	281.94
Cl^- (mg/L)	≤ 250	1008.38	283.39	413.99	1372.57
SO_4^{2-} (mg/L)	≤ 250	1431.25	354.50	700	1775
HCO_3^- (mg/L)	≤ 250	123.77	23.73	88.72	166.28
NO_2^- (mg/L)	≤ 0.5	1.88	3.44	0.00	10.00
NO_3^- (mg/L)	≤ 50	3.36	2.69	0.20	7.20
PO_4^{3-} (mg/L)	≤ 5	0.14	0.11	0.03	0.36
Total Fe (mg/L)	≤ 0.3	0.20	0.16	0.07	0.51
F^- (mg/L)	≤ 1.5	1.53	0.65	0.41	2.20

SD, standard deviation.

The pH is close to neutral, from 7.10 to 7.53 (mean 7.33 ± 0.14), and stays within the 6.5–8.5 range in every sample. Temperature ranges from 18.9 to 30.1 °C (mean 23.38 ± 5.25 °C), so that all but the warmest sample fall within the 12–30 °C range. Redox potential is slightly negative on average (−7.93 ± 8.47 mV), with values from −20.9 to +1.5 mV. Free CO_2 ranges from 13.89 to 101.89 mg/L (mean 32.42 ± 28.58 mg/L) and is above the 10 mg/L reference value in all samples.

The water is strongly mineralized. EC varies from 2210 to 5830 µS/cm (mean 4796 ± 1175 µS/cm), well above the 500–1500 µS/cm reference range, and no sample falls inside it. Salinity ranges from 1.1 to 3.2 g/L (mean 2.6 ± 0.68 g/L). TDS ranges from 1112 to 3080 mg/L, with a mean of 2395 ± 771 mg/L; even the lowest value is above the 1000 mg/L limit.

The same is true of most major ions. Calcium (240.48–521.04 mg/L; mean 422.84 ± 80.07 mg/L) and magnesium (109.37–281.94 mg/L; mean 227.55 ± 55.95 mg/L) are above their reference values of 100 and 50 mg/L in every sample. Magnesium is less abundant than calcium. Chloride (413.99–1372.57 mg/L; mean 1008.38 ± 283.39 mg/L) and sulfate (700–1775 mg/L; mean 1431.25 ± 354.50 mg/L) both exceed the 250 mg/L reference value throughout, and sulfate is the most abundant anion. Bicarbonate is the exception: it is low and fairly uniform (88.72–166.28 mg/L; mean 123.77 ± 23.73 mg/L) and remains

below 250 mg/L.

Nitrogen and phosphorus species, iron and fluoride, whose statistics are also given in Table 1, are treated in Section 4.3.

4.2 Factors controlling groundwater mineralization in the Terminal Complex

Groundwater samples from the Terminal Complex exhibited high mineralization, as reflected in their electrical conductivity (EC) and total dissolved solids (TDS). EC and TDS were positively correlated ($r = 0.79$, Fig. 4). Sulfate, chloride, calcium, and magnesium accounted for most of the measured ionic load. Correlation coefficients for the ion pairs in Table 2 ranged from 0.56 to 0.63.

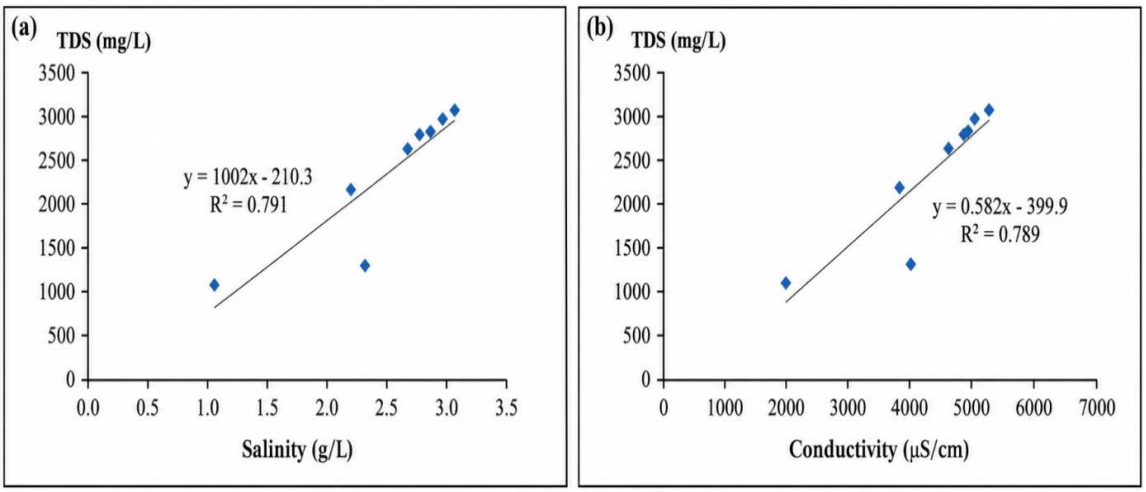


Fig. 4. Relationship of total dissolved solids (TDS) with salinity and electrical conductivity in groundwater samples from the Terminal Complex aquifer, Oued Righ valley.

Table 2. Correlations among variables associated with groundwater mineralization in the Terminal Complex.

Variable pair	Correlation coefficient (r)
Total dissolved solids–electrical conductivity	0.79
Calcium–magnesium	0.63
Calcium–sulfate	0.62
Sulfate–chloride	0.56

The positive calcium–sulfate correlation ($r = 0.62$, Fig. 5) is consistent with the dissolution of gypsum and anhydrite. This interpretation accords with the regional geology, which includes clay-rich and evaporitic formations containing both minerals (Bel and Demargne, 1966). Calcium and magnesium concentrations exceeded 500 and 250 mg/L, respectively, in some samples. The positive calcium–magnesium correlation ($r = 0.63$, Fig. 5) is also compatible with water–rock interactions involving carbonate minerals such as dolomite. Bicarbonate made a smaller contribution to the measured anionic load than sulfate and chloride.

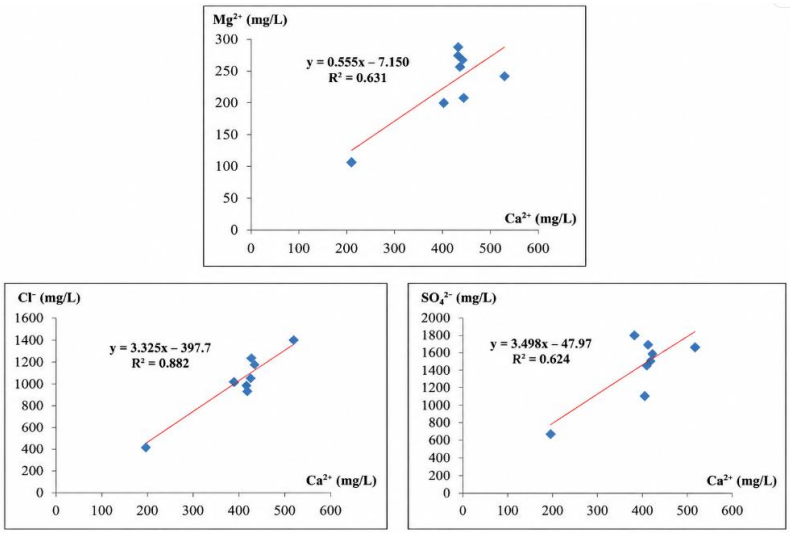


Fig. 5. Relationships of calcium (Ca^{2+}) with magnesium (Mg^{2+}), chloride (Cl^{-}), and sulfate (SO_4^{2-}) concentrations in groundwater samples from the Terminal Complex aquifer.

Expressed in milliequivalents per litre, the mean calcium and magnesium concentrations summed to 39.8 meq/L, while mean sulfate, chloride, and bicarbonate concentrations were 29.8, 28.4, and 2.0 meq/L, respectively. The ratio of mean molar calcium to mean molar sulfate was approximately 0.7, compared with the stoichiometric ratio of 1 expected from gypsum or anhydrite dissolution alone. The relative excess of sulfate is consistent with several processes, including cation exchange that modifies dissolved calcium concentrations (Cornet, 1964) and dissolution of other sulfate-bearing minerals.

Chloride averaged approximately 1,000 mg/L and contributed nearly as much as sulfate to the measured anionic charge. The two ions showed moderate positive covariation ($r = 0.56$). Taken together, the high sulfate and chloride concentrations, the calcium-to-sulfate molar ratio, and the regional lithology support a contribution from evaporite dissolution, with other water–rock interactions potentially modifying the ionic composition of groundwater along its flow paths.

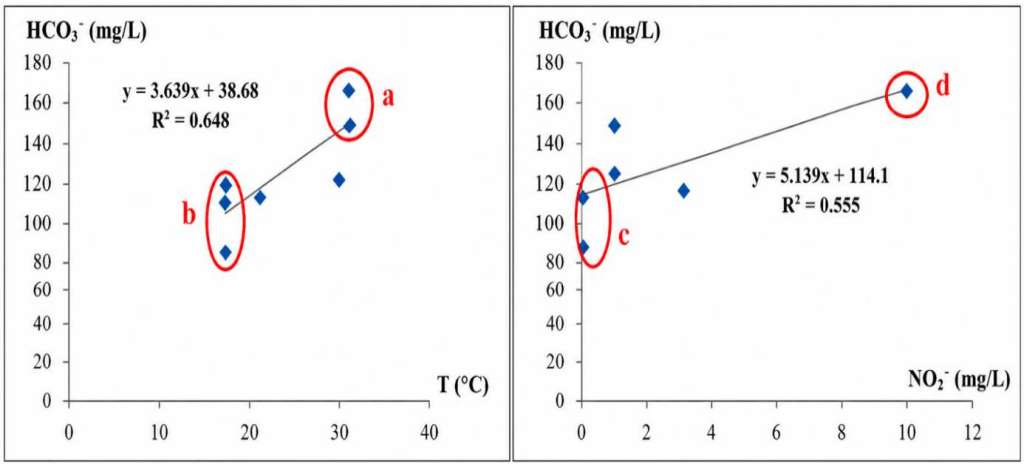


Fig. 6. Relationships between bicarbonate (HCO_3^-) concentration and temperature (T), and between bicarbonate (HCO_3^-) and nitrite (NO_2^-) concentrations in groundwater samples from the Terminal Complex aquifer.

4.3 Nitrite, fluoride and iron

Of the parameters in Table 1, three bear directly on whether the water can be drunk: nitrite, fluoride and iron. Fluoride is the most serious of the three.

a. Nitrite: Nitrate is low in all samples (0.20–7.20 mg/L; mean 3.36 ± 2.69 mg/L), far below the 50 mg/L limit. Nitrite is another matter. It ranges from 0.00 to 10.00 mg/L, and its mean (1.88 ± 3.44 mg/L) is almost four times the 0.5 mg/L limit. The standard deviation is larger than the mean, so the nitrite is concentrated in a subset of samples and absent from others. Nitrite is the form of nitrogen that matters most here, because it is the one that harms infants, whose blood loses oxygen-carrying capacity when they drink it (WHO, 2022).

b.

The weak correlation between nitrate and chloride ($r < 0.24$) gives no sign that mineral fertilizers are responsible. Nitrite is positively correlated with bicarbonate ($r = 0.56$; Fig. 6), which does not point to a source. The aquifer is normally protected from surface contamination by an impermeable layer, so the nitrite may enter through boreholes whose cement seal is imperfect, which would put the confined water in contact with the water above it. Orthophosphate is low (0.03–0.36 mg/L; mean 0.14 ± 0.11 mg/L) and meets the 5 mg/L reference value. It correlates moderately with EC ($r = 0.58$; Fig. 7).

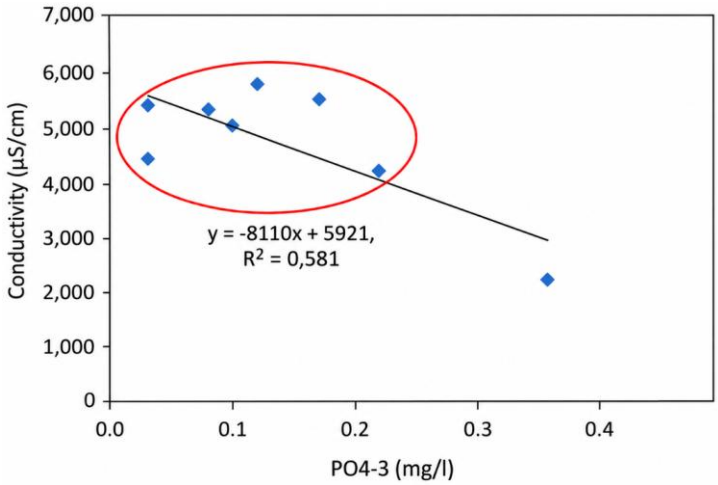


Fig. 7. Relationship between orthophosphate concentration and electrical conductivity (EC) in groundwater samples from the Terminal Complex aquifer, Oued Righ Valley, Algeria.

c. Fluoride: Fluoride ranges from 0.41 to 2.20 mg/L, and its mean (1.53 ± 0.65 mg/L) is slightly above the 1.5 mg/L limit. Some samples therefore exceed the limit by a wide margin and others fall well below it. Long-term consumption above this limit causes dental fluorosis, and in the worst cases skeletal damage (WHO, 2022). The amount of fluoride in water depends mainly on how long it stays in contact with fluorine-bearing minerals in the aquifer. Phosphate minerals are a probable supplier, which fits the moderate correlation with orthophosphate (r = 0.51). Fluoride also correlates with sulfate, total iron, calcium, temperature and redox potential (r = 0.41–0.59; Fig. 8), but these are moderate links, and they point to indirect relationships and do not identify a source.

d. Iron: Iron is lower in concentration than fluoride but has a clear effect on water quality. It ranges from 0.07 to 0.51 mg/L (mean 0.20 ± 0.16 mg/L), so the average is below the 0.3 mg/L limit, while some samples exceed it. At these levels iron does not harm health, but it encourages bacterial growth and corrodes pipes. Iron correlates with sulfate (r = 0.83), orthophosphate (r = 0.79), temperature and EC (both r = 0.70) and calcium (r = 0.50; Fig. 8). These relationships show that iron varies together with the mineralization of the water. Natural sources in the rock may explain it, and drilling can also raise iron concentrations in groundwater.

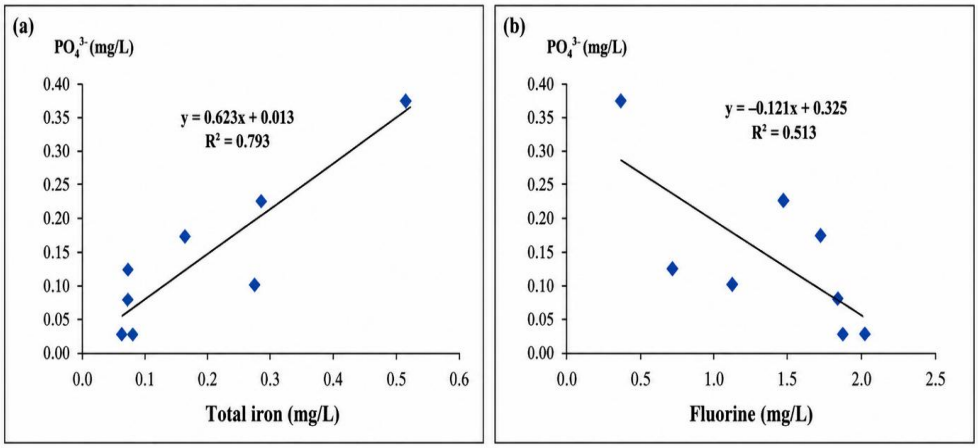


Fig. 8. Relationships between orthophosphate (PO_4^{3-}) concentration and total iron and fluoride concentrations in groundwater samples from the Terminal Complex aquifer, Oued Righ Valley, Algeria.

4.4 Soils: pH, salinity and ionic composition

Table 3 gives the statistics of the soil solution. Soil pH is moderately variable, whereas conductivity and the ion concentrations vary widely from one site to another.

Table 3. Descriptive statistics of the soil solution in the Oued Righ valley.

	pH	EC (dS/m)	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
Mean	7.68	16.84	3.47	1.26	84.10	254.76	43.38	70.18	190.48	5.36
SD	0.33	20.86	2.45	13.91	143.41	421.20	10.19	115.71	310.54	9.43
Min	6.00	3.01	0	0	4	11	6	3.5	1.8	0
Max	8.80	146	15	184	1776	3610	85	1050	2775	65
CV (%)	4	124	70	1107	171	165	23	165	163	176

Ions in meq/L. SD, standard deviation; CV, coefficient of variation.

a. pH: Soil pH ranges from 6.0 to 8.8 (mean 7.68 ± 0.33). The kriged map (Fig. 9) shows that most of the valley is weakly alkaline, with a pH between 7.4 and 7.8. Moderately alkaline soils (7.9–8.4) occur around Sidi Slimane and Megarine, southwest of Blidet Amor, and in the north of the valley at Chott Merouane. Between Djamaa and M'Ghaier the soils are neutral to weakly acidic, and in the extreme southwest of Blidet Amor they are strongly alkaline (pH ≥ 8.5). All of these values lie within the range that plants tolerate, since none survives below pH 3 or above 9, although most cultivated plants do best between 5.5 and 6.5, so most of the soils are more alkaline than the optimum.

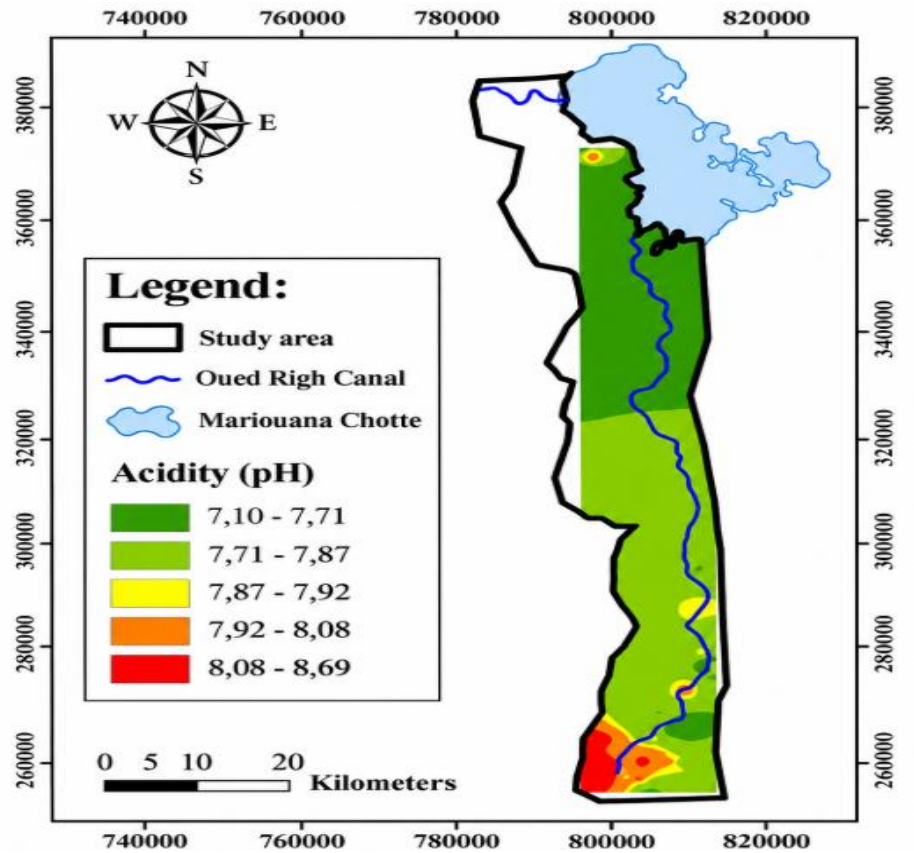


Fig. 9. Spatial distribution of soil pH in the Oued Righ valley obtained by kriging.

b. Salinity: Electrical conductivity of the soil solution averages 16.84 ± 20.86 dS/m and ranges from 3.01 to 146 dS/m (Fig. 10). The spread is as telling as the mean: the coefficient of variation is 124%, and the highest values are about nine times the average. Among the ions, chloride (mean 254.76 meq/L) and sodium (190.48 meq/L) have the highest mean concentrations of the anions and cations, respectively, followed by sulfate (84.10 meq/L) and magnesium (70.18 meq/L). Calcium (43.38 meq/L) is less abundant, and bicarbonate, carbonate and potassium are minor. Every ion except calcium has a coefficient of variation above 100%, so salts are very unevenly distributed across the valley.

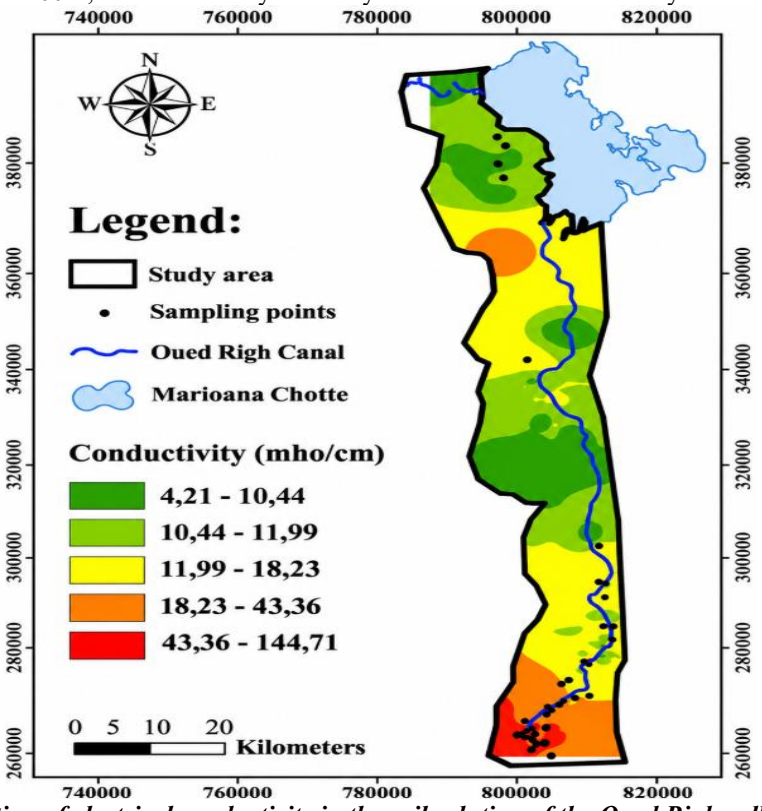


Fig. 10. Spatial distribution of electrical conductivity in the soil solution of the Oued Righ valley obtained by kriging.

c. Ionic composition. To see which ions go together, we correlated each cation with each anion across the soil samples (Table 4). Sodium and chloride vary almost in step (r = 0.985). Magnesium and potassium also follow chloride closely (r = 0.90 and 0.87). The sulfate pairs are moderate, at about 0.52–0.57, and bicarbonate is only weakly linked to the cations. Calcium is the outlier, with no clear relationship to any anion (r ≤ 0.07).

Table 4. Correlation coefficients between cations and anions in the soil solution.

	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Cl^-
Ca^{2+}	0.067	0.004	0.025	0.065
Mg^{2+}	0.405	0.000	0.546	0.900
Na^+	0.321	0.000	0.522	0.985
K^+	0.067	0.067	0.566	0.869

Conductivity follows the same ions. It is most closely tied to chloride (r = 0.95) and sodium (r = 0.94), then to potassium (0.88), sulfate (0.76) and magnesium (0.74). The kriged maps of conductivity, cations and anions show similar spatial patterns (Fig. 11), and conductivity rises steadily with the chloride content of the soil solution (Fig. 12).

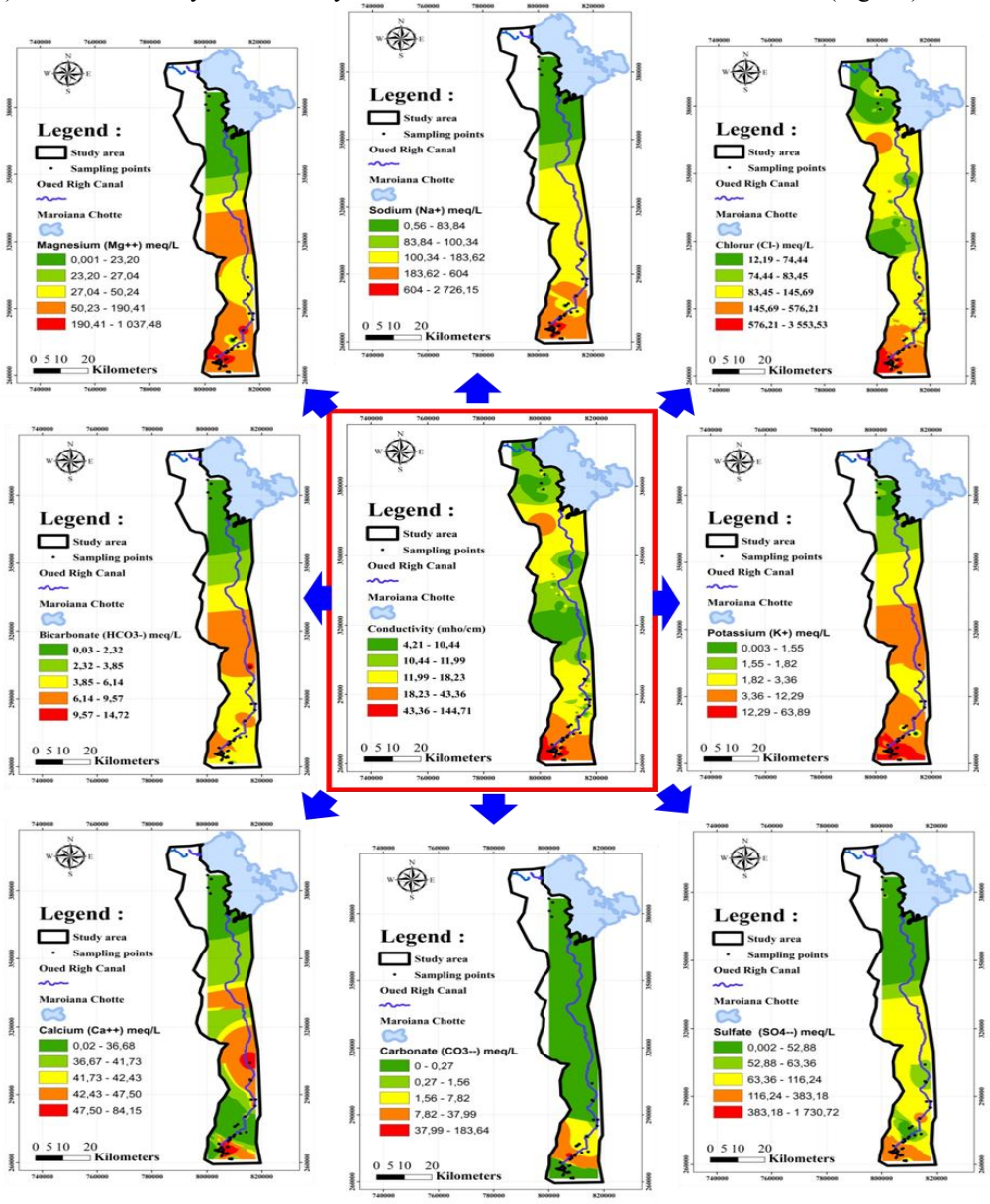


Fig. 11. Kriging maps showing the spatial distribution of electrical conductivity and major cations and anions in the Oued Righ soil solution.

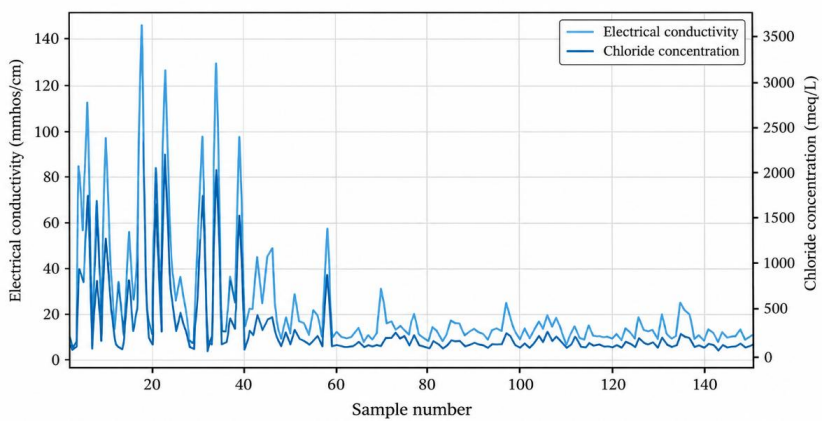


Fig. 12. Variation in soil-solution electrical conductivity and chloride concentration across the 151 sampled sites.

4.5 Nature of the salts

The salt obtained by evaporating a soil extract (Section 3.4) was analyzed by EDX. The spectrum (Fig. 13) is dominated by chlorine (64.55 wt%; 50.04 at%) and sodium (27.88 wt%; 33.33 at%). Carbon (7.08 wt%), sulfur (0.38 wt%) and aluminium (0.10 wt%) are minor, and magnesium, potassium and calcium do not appear.

Sodium and chlorine are therefore the main constituents of the residue, which is consistent with sodium chloride as its principal component. The match is incomplete, though. The atomic Na/Cl ratio is 0.67, against 1.00 for pure NaCl, so the detected sodium balances about two-thirds of the chlorine, and the rest is not matched by any cation in the spectrum. Magnesium and potassium follow chloride closely in the soil solution (r = 0.90 and 0.87; Table 4), and they may be present below the detection of this analysis. The semi-quantitative nature of EDX may also explain the gap, and this single spectrum cannot settle which.

Sulfur is nearly absent from the residue, even though sulfate is the second most abundant anion in the soil solution (84.10 meq/L, against 254.76 meq/L for chloride). Carbon is a light element that EDX measures poorly, and its origin (organic matter, carbonate or sample mounting) cannot be established here.

The result rests on one spectrum, gives elements and not mineral phases, and is semi-quantitative. X-ray diffraction of the same residue would identify the phases present.

Spectrum: Acquisition

Element	Series	Net unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (3 Sigma) [wt.%]
chlore	K-series	12851	54.90	64.55	50.04	5.89
sodium	K-series	3438	23.72	27.88	33.33	5.10
aluminium	K-series	15	0.09	0.10	0.10	0.15
carbone	K-series	31	6.02	7.08	16.20	14.95
soufre	K-series	91	0.33	0.38	0.33	0.19
	Total:		85.05	100.00	100.00	

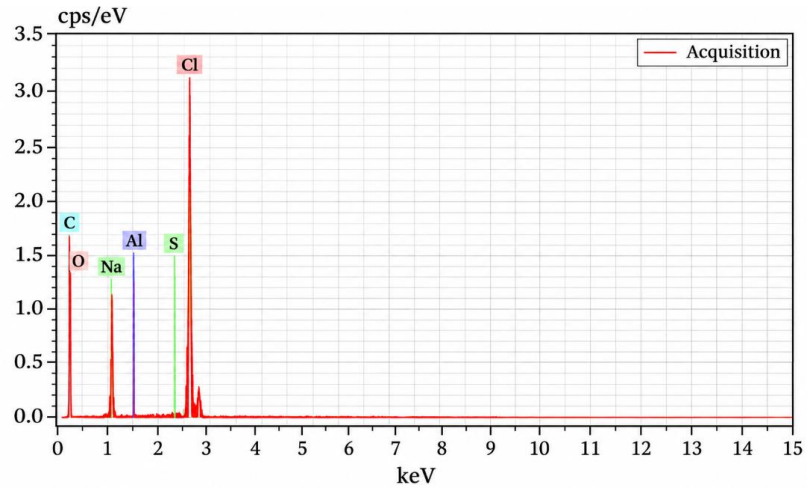


Fig. 13. EDX spectrum of the salt residue extracted from the soil sample.

4.6 From aquifer to soil

Two different salt signatures. The water that irrigates the valley and the solution found in its soils do not carry the same salts. In the Terminal Complex water, sulfate and chloride are present in roughly equal amounts (means of 29.8 and 28.4 meq/L), with calcium and magnesium the measured cations. In the soil solution, chloride (254.76 meq/L) and sodium (190.48 meq/L) are far ahead of every other ion, and sulfate (84.10 meq/L) comes well behind them.

Absolute concentrations cannot be compared, because the soil extracts are diluted by the extraction itself. Proportions can (Table 6). Chloride makes up about 47% of the anions in the water and 74% in the soil solution, while sulfate falls from 49% to 24%. Calcium falls from 53% to 38% of the calcium plus magnesium. These figures come from the means of two sample sets that are not paired, so they describe a tendency across the valley and not a change followed at any one site.

Table 6. Relative composition of the TC groundwater and the soil solution, calculated from mean concentrations in meq/L (% of the sum of anions, or of $Ca^{2+} + Mg^{2+}$).

	TC groundwater	Soil solution
Cl^-	47	74
SO_4^{2-}	49	24
$HCO_3^- + CO_3^{2-}$	3	1
$Ca^{2+} / (Ca^{2+} + Mg^{2+})$	53	38

A hypothesis. Calcium sulfate is much less soluble than sodium chloride. As water evaporates, gypsum should therefore crystallize early, whereas sodium and chloride stay dissolved until the solution is far more concentrated. Water that evaporates repeatedly at the soil surface would end up poorer in calcium and sulfate and richer in sodium and chloride than the water that fed it, which is the direction of the shifts in Table 6. The EDX spectrum of the residue, dominated by chlorine and sodium with very little sulfur (Fig. 13), and the close tie between soil conductivity and chloride and sodium ($r = 0.95$ and 0.94) are in line with this picture.

The data cannot confirm it. The sequence would have to be followed on paired samples of irrigation water, shallow water table and soil taken at the same sites, and tested with saturation indices for gypsum and halite. Other factors we did not measure, such as drainage, the depth of the water table and the amount of irrigation, may matter as much. Koull et al. (2013) found sulfated–calcic facies in soils of the same valley, so a comparison with our soils would require the same classification to be applied to both sets of data.

Drinking. TDS, EC, calcium, magnesium, chloride and sulfate exceed their reference values in every sample, and nitrite, fluoride and iron do so in some. The water is not suitable for drinking.

Irrigation. The EC of the water ranges from 2.21 to 5.83 dS/m, well above the 0.5–1.5 dS/m reference range of Table 1. Chloride averages 1008 mg/L, and in high concentrations it damages plant tissues and leaves. Neutral salts also accumulate in the soil with irrigation, and they reduce the water available to plants. The risk from sodium cannot be judged, because sodium and potassium were measured but not reported, and the sodium adsorption ratio was not calculated. On soils that are already highly saline, this water adds salt each time it is applied, so its use depends on leaching and drainage.

Limits of the study. Water and soil samples are not paired by borehole and plot. Sodium and potassium are missing from the water results. EDX is semi-quantitative and does not identify minerals, the extraction ratio of the soil solution is not given, and the study represents a single moment. A Piper diagram, saturation indices, the sodium adsorption ratio and X-ray diffraction of the salts would address most of these gaps.

5. Conclusions

The Terminal Complex groundwater of the Oued Righ valley is close to neutral but strongly mineralized. EC ranges from 2210 to 5830 µS/cm and TDS from 1112 to 3080 mg/L. Calcium, magnesium, chloride and sulfate exceed their reference values in every sample, while bicarbonate stays low. The link between calcium and sulfate ($r = 0.62$), together with the clay, gypsum and anhydrite formations the water crosses, is consistent with the dissolution of gypsum and anhydrite. That cannot be the only source. The mean Ca/SO_4 molar ratio is about 0.7 and not 1, and chloride is nearly as abundant as sulfate. Cation exchange and other evaporite minerals may contribute, but these data cannot separate them.

Three constituents matter for drinking. Nitrite averages 1.88 mg/L against a limit of 0.5 mg/L, fluoride averages 1.53 mg/L and reaches 2.20 mg/L, and iron exceeds 0.3 mg/L in some samples. Nitrate and orthophosphate are low. The water is not suitable for drinking.

The soils are mostly weakly alkaline (pH 7.4–7.8) and very unevenly salinized: the EC of the soil solution runs from 3.01 to 146 dS/m. Chloride and sodium have the highest mean concentrations among the anions and cations, and they vary almost in step ($r = 0.985$). EC follows them closely ($r = 0.95$ with chloride, 0.94 with sodium). The EDX spectrum of the evaporation residue is dominated by chlorine and sodium, with an atomic Na/Cl ratio of 0.67, and magnesium, potassium and calcium do not appear in it. Compared with the groundwater, the soil solution carries proportionally more chloride (74% of the anions against 47%) and less sulfate (24% against 49%). This agrees with sodium chloride accumulating at the surface after gypsum

has precipitated early during evaporation, but it does not demonstrate it.

As irrigation water, the TC water (EC 2.21–5.83 dS/m, chloride about 1000 mg/L) can only be used with leaching and drainage, and its sodium hazard has not been assessed. Establishing the link between water and soil would take paired samples of irrigation water, shallow water table and soil, sodium and potassium results for the water, saturation indices, the sodium adsorption ratio and X-ray diffraction of the salts.

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