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RESEARCH ARTICLE

USE OF IN SITU ANALYSES TO ASSESS SALINITY RISK IN THE INTERDUNE DEPRESSIONS OF THE SOUTHERN KORAMA VALLEY (NIGER)

UTILISATION DES ANALYSES IN SITU DANS LA DETERMINATION DU RISQUE DE SALINITE DANS LES CUVETTES DU VERSANT SUD DE LA KORAMA (NIGER)

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Abstract

Background: Since the mid-1990s, the return of rainfall in the southern strip of the Korama valley, south of Zinder (Niger), has led to a hydrological recovery, followed by a phenomenon still new to the area: the salinization of water in interdune depressions.

Methods: Water from 21 interdune depressions was analysed in situ during two field campaigns, at the beginning (January) and at the end (April) of the 2026 dry season; both campaigns are complete for 20 depressions. Electrical conductivity (EC), salinity and pH were measured with a calibrated portable multiparameter tester. Seasonal differences were tested with the Wilcoxon signed-rank test. A salinization risk index (SRI) based on the USSSL EC classes was mapped by depression, and the EC of depression water was compared with that of the alluvial aquifer recorded at 23 piezometers (2015–2022).

Results: EC varied widely between depressions, from 0.07 to 5.01 dS/m in January and from 0.07 to 19.6 dS/m in April. Mean EC doubled (from 2.16 ± 1.52 to 4.36 ± 5.43 dS/m), but the median did not change (1.82 and 1.77 dS/m): EC rose in 12 depressions and fell in 8, and the paired difference was not significant overall ($p = 0.11$). It was significant in Bandé ($p = 0.012$), where 7 of the 12 depressions reached USSSL class C5 (> 5 dS/m) in April, with 19.6 dS/m at Kaba001. pH increased in 18 of the 20 depressions (median from 7.66 to 8.52; $p < 0.001$) and exceeded 9 in six. In April, seven depressions entailed severe restrictions for irrigation and four were of limited use or not recommended for livestock watering. Depression water was about 15 times more mineralized than groundwater (median 0.12 dS/m).

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Conclusion: Salinization of depression water is local: strong and seasonal in Bandé, moderate and stable in the four depressions sampled in Dungass, and low in Kwaya. The contrast with weakly mineralized, near-neutral groundwater points to the concentration of salts by evaporation in shallow surface water fed by the alluvial aquifer; the origin of the salts remains to be established by major-ion analyses. At the end of the dry season, when market gardening most needs water, the most saline depressions threaten the main productive asset of rural households.

Introduction:-

In arid and semi-arid regions, salinization of water and soils is one of the main drivers of land degradation. Dissolved salts become concentrated through evaporation, all the more rapidly where the water table is shallow or where irrigation relies on already saline water (Ayers & Westcot, 1985; Shokri et al., 2024). Endorheic basins are particularly exposed, since water has no outlet. Salinity increases towards the terminal low points, where mineral dissolution and evapotranspiration combine (Wang et al., 2025).

In the central Sahel, rainfall has recovered since the mid-1990s. Surface runoff has increased and water tables have risen, a pattern known as the “Sahelian hydrological paradox” (Descroix et al., 2018; Leblanc et al., 2008). In the southern strip of the Korama valley, in the south of the Zinder region, the water bodies of the interdune depressions of Kwaya, Bandé and Dungass have been expanding ever since. In 2024, during a survey of 293 households, many farmers spontaneously reported that the water in the depressions was deteriorating and that salt crusts were appearing along the banks.

In Niger, salinity was first studied in irrigated soils of the Niger River valley. Guero and Bozza (1992) linked soil fertility and salinity in the Sahelian and Saharan zones of the country. At Kollo, Ducloux et al. (1994) described the mineralogy of salt efflorescences in paddy soils, and Issifou Adam (2011) produced a fine-scale map of salinity in an irrigation scheme, showing a spatial structure that remained stable from one season to the next. In eastern Niger, the oasis depressions of the Manga, in the department of Gouré, provide the closest analogue to our study area. Barké et al. (2017) interpret them as remnants of a drainage network dismantled by dunes, much like the interdune depressions of the Korama. Ambouta et al. (2018) observed higher groundwater mineralization at the centre than at the margins of the depressions, a sodium bicarbonate facies at Iskour, and a recent infill capped by an evaporitic layer up to about twelve metres thick; at the centre of the Balla depression, the water is unfit for drinking and of poor quality for irrigation. In depressions with a shallow water table, natron crusts form during the dry season and are harvested every year (Illou, 2018), and farmers list salinity among their production constraints (Malam Assane et al., 2021).

In the Korama basin, research has focused mainly on groundwater. The mineralization of water in the Zinder region and the geochemistry of the Continental Terminal and Korama aquifers are well documented (Amadou et al., 2014; Issa et al., 2015; Souley Moussa et al., 2018): electrical conductivity ranges from a few tens to more than 2,000 $\mu\text{S}/\text{cm}$ depending on the aquifer, controlled by residence time and mineral dissolution, whereas the Korama aquifer remains weakly mineralized (35–83 $\mu\text{S}/\text{cm}$; Issa et al., 2015). In the upper basin, at Droum, the phreatic aquifer is very weakly mineralized (EC of 23–246 $\mu\text{S}/\text{cm}$) and suitable for irrigation (Souleymane et al., 2020a); stable isotopes reveal recharge water bearing an evaporation signature, as well as exchanges between aquifers (Sandao et al., 2018). Studies at Dogo-Dogo and Gouchi characterized the hydrogeology and sanitary quality of groundwater, with guideline exceedances mainly involving arsenic, nitrate and bacteria (Souleymane et al., 2022, 2024). In the neighbouring Goulbi N’Kaba valley, mineralization of the alluvial aquifer increases from upstream to downstream with water–rock contact time (Yahouza et al., 2018). By contrast, to our knowledge, the surface waters of the Korama depressions have never been monitored: neither their chemistry, nor its seasonal variations, nor their implications for irrigation and livestock watering. These depressions are far from any laboratory and outside any monitoring network. A portable instrument used directly in the field makes it possible to overcome this constraint. This paper describes the salinity of water in 21 depressions of the southern Korama strip based on in situ physico-chemical measurements, and derives a salinization risk index for each depression. The specific objectives are (i) to measure how EC, salinity and pH change between the beginning and the end of the dry season, and to test whether this change is statistically significant; (ii) to assess these waters against international standards for irrigation and livestock watering; and (iii) to map the risk by depression and to compare the mineralization of surface water with that of the underlying aquifer.

Materials and Methods:-

Study area:-

The study area comprises the rural communes of Kwaya and Bandé (Magaria department) and Dungass (Dungass department), in the south of the Zinder region, on the border with Nigeria (Figure 1). The land slopes down from west (Kwaya) to east (Dungass), which is the direction in which water would flow if the endorheic regime were to break down.

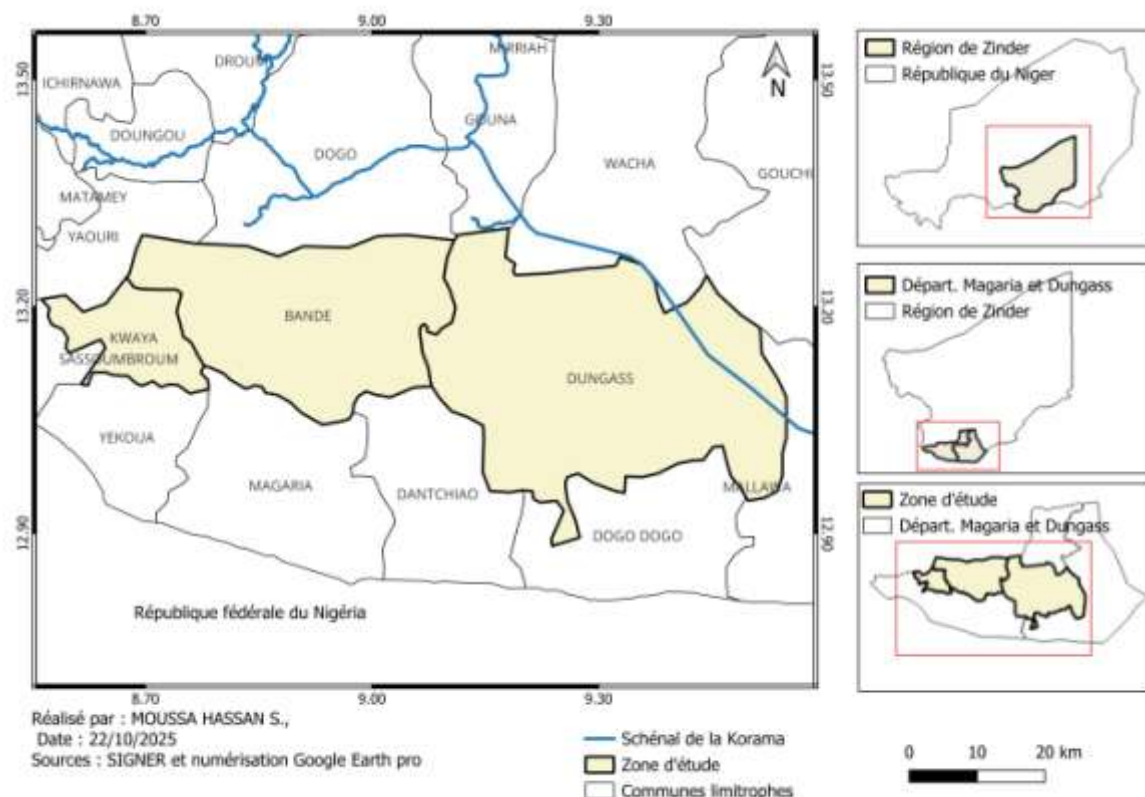


Figure 1: Location of the study area

Source: SIGNER and Google Earth Pro digitization; map: Moussa Hassan S., 2025

The area lies on the Continental Terminal of the Iullemmeden Basin, composed of clayey sandstones and fine sands, which may locally contain saline, evaporitic or carbonate horizons; these have not been characterized in the study area. These formations host the Korama alluvial aquifer, whose depth generally ranges from 0 to 20 m (Souleymane et al., 2020b) and which lies close to the surface in most lowlands: in the piezometers of the study area, the median depth to water ranged from 0.85 to 5.07 m in 2014–2023 (Section 3.7). Groundwater and surface water therefore interact very rapidly. During the rainy season, the depressions recharge the aquifer; subsequently, the rising water table keeps the wetlands flooded long after the last rains (Alpha Gado, 2021).

The landscape is dominated by Quaternary dunes, mostly transverse (Malam Abdou, 2014). Closed depressions lie between them, each functioning as a small endorheic basin, like the oasis depressions of the Manga, whose shape and orientation are controlled by dune ridges (Barké et al., 2017). Soils are sandy on dune crests, sandy-loam in market-garden depressions and sandy-clay in some plains; the lowlands bear more clayey hydromorphic soils. The climate is Sahelo-Sudanian, with 400–600 mm of annual rainfall from June to September. The ensuing dry season is long and hot, with high evapotranspiration. After the droughts of the 1970s and 1980s, rainfall recovered from 1994 onwards and extreme rainfall totals became more frequent, notably in 2020 and 2024. The flooded areas of the depressions then expanded considerably.

Selection of sampling sites:-

The network comprises 21 depressions, selected purposively among the water bodies used for market gardening: 13 in Bandé, 4 in Kwaya and 4 in Dungass (Figure 2). It is not intended to be representative of all depressions in the area, many of which show no visible salinity. Bandé has more because the commune contains most of the permanent and semi-permanent depressions visible on Sentinel imagery. The sites correspond to the ten villages of the 2024 household survey, plus the administrative centres of Bandé and Kwaya, allowing water chemistry to be compared directly with residents' perceptions. All selected depressions have high water potential and lie in sectors from which the communal agricultural services receive requests for land reclamation support. Both campaigns are complete for 20 depressions (12 in Bandé, 4 in Kwaya and 4 in Dungass), which are used in all analyses. Each measurement point was located with a handheld GPS (WGS 84); the coordinates of the depressions are given in Appendix Table A1.

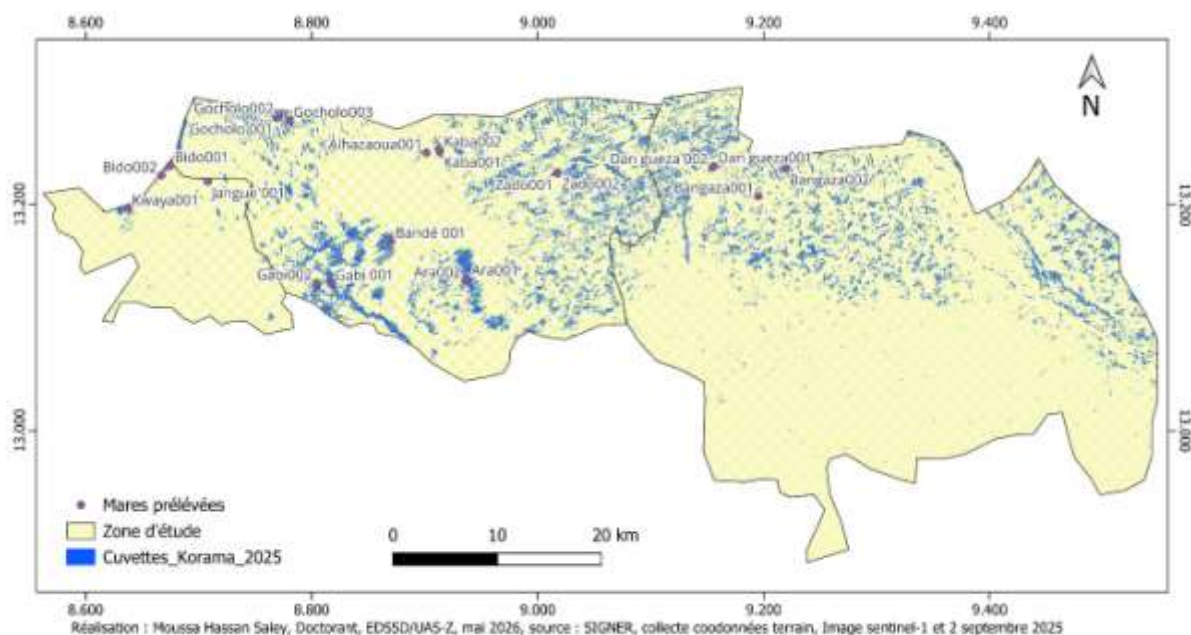


Figure 2: Location of the 21 depressions sampled in January and April 2026

Map: Moussa Hassan S., May 2026; sources: SIGNER, field GPS surveys, Sentinel-1 and Sentinel-2 imagery (September 2025)

At each depression, the measurement point had to meet three conditions. First, it had to be away from areas of livestock trampling, washing and domestic discharge. Second, the water had to be deep enough to immerse the probe and the bottle without touching the bottom, since resuspended sediment would have biased the measurement. Third, the point was located in the widest part of the water body, so that the sample represented the main water mass.

Sampling strategy and measurement protocol:-

Two campaigns were conducted in 2026. In January, at the beginning of the dry season, the depressions still hold a large volume of water after the rains. In April, the dry season is well advanced: evaporation accumulated since October–November has greatly reduced their volume and concentrated dissolved constituents. The comparison between the two campaigns is therefore expected to reflect the effect of evaporative concentration, which was not measured directly, since water volumes were not monitored.

Measurements were taken with a waterproof (IP67) pen-type multiparameter water quality meter, model C-600 (also labelled COM-600; manufacturer not stated), which reads EC, total dissolved solids (TDS), salinity, specific gravity, oxidation–reduction potential, pH and temperature, with automatic temperature compensation (0–60 °C). According to the manufacturer, EC is measured from 0 to 10,000 $\mu\text{S}/\text{cm}$ and from 10.1 to 400.0 mS/cm (effective range up to 200 mS/cm), with a resolution of 1 $\mu\text{S}/\text{cm}$ or 0.1 mS/cm and an accuracy of $\pm 2\%$ of full scale; pH is measured from 0 to 14.00, with a resolution of 0.01 and an accuracy of ± 0.05 pH unit; temperature accuracy is ± 0.5 °C. Before each campaign, the pH electrode was calibrated at three points with buffer solutions (pH 4.01, 6.86 and 9.18), each

prepared by dissolving the powder sachet in 250 mL of water at 25 °C; EC was measured with the factory calibration, the meter allowing recalibration with standard solutions of 1,413 $\mu\text{S}/\text{cm}$, 12.88 mS/cm and 111.3 mS/cm . The probe was rinsed thoroughly with distilled water between sites. Water was collected in 2 L plastic bottles, rinsed three times with depression water. It was then poured into a beaker rinsed in the same way, into which the electrodes were immersed; readings were recorded once the values had stabilized (Figure 3). All measurements were made in the field immediately after sampling; no sample was analysed in a laboratory.

EC is reported in dS/m throughout ($1 \text{ dS}/\text{m} = 1 \text{ mS}/\text{cm} = 1,000 \mu\text{S}/\text{cm}$). The instrument derives TDS from EC with a fixed factor of 0.5 ($\text{TDS in ppm} = 0.5 \times \text{EC in } \mu\text{S}/\text{cm}$) and also computes salinity (displayed in %) from EC; these two variables therefore carry no information independent of EC. TDS is not analysed as a separate variable, and salinity is reported for information only.



Figure 3: Measurement protocol: (a) sampling in the Kwaya depression; (b) water stored in a bottle; (c) multiparameter meter Photographs: Moussa Hassan S., January 2026

Data processing and interpretation:-

Data processing was carried out in four steps. First, for each parameter and campaign, the mean, standard deviation (SD), coefficient of variation (CV), median, interquartile range (IQR), minimum and maximum were calculated over the 20 depressions, together with the April/January EC ratio of each depression, which indicates the magnitude of seasonal change. Because the sample is small and EC values are strongly right-skewed, the seasonal difference was tested with the two-sided exact Wilcoxon signed-rank test for paired samples (Wilcoxon, 1945), for all depressions and by commune; differences between communes were explored with the Kruskal–Wallis test (Kruskal & Wallis, 1952), as an indication only given the group sizes (4–12). Statistics were computed in Python with SciPy (Virtanen et al., 2020), at a significance level of 0.05. Second, the waters were classified according to several standards (Table 1): the USSS salinity classes based on EC (Richards, 1954), and the restrictions on irrigation water use and the guidelines for saline water for livestock and poultry (Ayers & Westcot, 1985).

Table 1: Classification thresholds used

Standard	Parameter	Classes and thresholds
USSS (Richards, 1954)	EC	C1 < 0.25; C2: 0.25–0.75; C3: 0.75–2.25; C4: 2.25–5; C5 > 5 dS/m
FAO, irrigation (Ayers & Westcot, 1985)	EC	No restriction < 0.7; slight to moderate restriction: 0.7–3; severe restriction > 3 dS/m
FAO, livestock watering (Ayers & Westcot, 1985)	EC	Excellent < 1.5; very satisfactory: 1.5–5; unfit for poultry: 5–8; limited use: 8–11; very limited use: 11–16; not recommended > 16 dS/m
Alkalinity	pH	pH > 8.5: alkaline water; the sodicity hazard cannot be assessed without SAR

Sources: Richards (1954); Ayers & Westcot (1985)

The third step was the calculation of a salinization risk index (SRI) for each depression and each campaign. The SRI is the score of the USSS EC class, from 1 (C1, < 0.25 dS/m) to 5 (C5, > 5 dS/m), grouped into four levels: low (1–

2), moderate (3), high (4) and critical (5). It relies on EC alone because EC is the only independent measure of mineralization provided by the instrument: TDS and salinity are derived from it, and combining them with EC would count the same information twice. The USSSL classes were retained because they are the reference thresholds for the salinity hazard of irrigation water, defined from crop salt tolerance and leaching requirements (Richards, 1954), and they are consistent with the FAO guidelines (Ayers & Westcot, 1985). The full USSSL classification crosses EC classes (C) with sodium adsorption ratio classes (S); without SAR, the SRI expresses the salinity hazard only, not the sodicity hazard. Finally, the SRI of each depression was mapped as a point symbol for each campaign, without interpolation. Inverse distance weighting was not retained: the depressions are closed, hydrologically independent basins, and 21 unevenly distributed points (only four in Kwaya and four in Dungass, the latter all in the west of the commune) cannot support a continuous surface, which would assign a salinity level to areas where nothing was measured.

Groundwater data:-

To compare surface water with the underlying aquifer, depth to water, EC and pH records of the Korama aquifer were obtained from the piezometric monitoring network of the Regional Directorate of Hydraulics of Zinder (DRH Zinder, 2026), which comprises 70 piezometers and 1,900 records from 1990 to 2023; EC and pH have been recorded since 2015. The piezometers located in the study area or within a 10-km buffer around it (WGS 84 / UTM 32N), on Nigerien territory, were selected; 23 of them have at least ten records in 2014–2023 (12 in the study area, none of which is in Kwaya, and 11 in the buffer). None is located in a depression. EC values recorded in mS/cm were converted to $\mu\text{S/cm}$, obviously erroneous values ($\text{EC} < 20 \mu\text{S/cm}$, $\text{pH} > 14$) were discarded, and the median EC of each piezometer was calculated over 2015–2022. The trend in depth to water was tested with the Mann–Kendall test and quantified by Sen's slope (Mann, 1945; Kendall, 1975; Sen, 1968). Because records are irregular (two to four per year, none in 2017), trends are indicative.

Results:-

Seasonal change in water quality: strong contrasts between depressions:-

Table 2 presents the values measured in the 20 depressions with complete data, and Table 3 summarizes their distribution and the results of the paired tests. Mineralization differs widely from one depression to another: in January, EC ranges from 0.07 dS/m (Kwaya001) to 5.01 dS/m (Kaba002 and Ara001), and in April from 0.07 to 19.6 dS/m (Kaba001). Between the two campaigns, mean EC doubles (from 2.16 ± 1.52 to 4.36 ± 5.43 dS/m), whereas the median hardly changes (1.82 then 1.77 dS/m). The mean is driven by a few depressions: EC increases in 12 depressions and decreases in 8, and the paired difference is not significant over the 20 depressions ($p = 0.11$). The coefficient of variation rises from 71% to 124%: the dry season widens the differences between depressions rather than raising salinity everywhere.

Table 2: EC, salinity and pH measured in the 20 depressions with complete data (January and April 2026)

Depression (commune)	EC Jan. (dS/m)	EC Apr. (dS/m)	Apr./Jan. n. EC ratio	Salinity Jan. / Apr. (%)	pH Jan.	pH Apr.	SRI Jan. / Apr.
Kaba001 (Bandé)	3.27	19.60	6.0	0.16 / 1.13	8.20	9.80	4 / 5
Kaba002 (Bandé)	5.01	12.94	2.6	0.25 / 0.70	8.10	9.53	5 / 5
Zado001 (Bandé)	2.20	12.23	5.6	0.11 / 0.65	8.32	9.71	3 / 5
Gocholo003 (Bandé)	3.66	10.52	2.9	0.18 / 0.55	9.18	9.64	4 / 5
Ara002 (Bandé)	3.17	6.37	2.0	0.16 / 0.32	8.00	8.52	4 / 5
Ara001 (Bandé)	5.01	5.98	1.2	0.25 / 0.30	9.14	9.18	5 / 5
Alhazaoua001 (Bandé)	4.61	5.13	1.1	0.23 / 0.25	7.89	9.44	4 / 5
Gocholo001 (Bandé)	2.43	2.76	1.1	0.12 / 0.13	7.69	8.18	4 / 4
Gocholo002 (Bandé)	1.66	1.70	1.0	0.08 / 0.08	7.68	8.17	3 / 3
Gabi002 (Bandé)	0.25	0.53	2.1	0.01 / 0.02	7.66	7.74	2 / 2
Bandé001 (Bandé)	0.49	0.41	0.8	0.02 / 0.02	7.15	8.24	2 / 2

Depression (commune)	EC Jan. (dS/m)	EC Apr. (dS/m)	Apr./Jan. n. EC ratio	Salinity Jan. / Apr. (%)	pH Jan.	pH Apr.	SRI Jan. / Apr.
Gabi001 (Bandé)	0.78	0.17	0.2	0.03 / 0.04	7.08	7.56	3 / 1
Jangué001 (Kwaya)	1.46	0.67	0.5	0.07 / 0.03	7.35	7.14	3 / 2
Bido001 (Kwaya)	1.38	0.50	0.4	0.06 / 0.02	7.46	6.86	3 / 2
Bido002 (Kwaya)	0.50	0.46	0.9	0.02 / 0.02	7.15	7.96	2 / 2
Kwaya001 (Kwaya)	0.07	0.07	0.9	0.00 / 0.00	7.30	7.60	1 / 1
Bangaza001 (Dungass)	1.90	2.97	1.6	0.09 / 0.15	7.38	8.95	3 / 4
Dan Guéza001 (Dungass)	1.78	1.84	1.0	0.08 / 0.09	7.43	8.65	3 / 3
Dan Guéza002 (Dungass)	1.65	1.50	0.9	0.08 / 0.07	7.35	8.71	3 / 3
Bangaza002 (Dungass)	1.86	0.96	0.5	0.09 / 0.04	7.66	8.53	3 / 3
Mean $\pm$ SD (20)	2.16 $\pm$ 1.52	4.36 $\pm$ 5.43	–	0.10 / 0.23	7.76 $\pm$ 0.60	8.51 $\pm$ 0.87	3.20 / 3.35
Median (20)	1.82	1.77	1.1	0.08 / 0.08	7.66	8.52	3 / 3

Source: in situ measurements, Moussa Hassan S., 2026. SRI: score of the USSL EC class, from 1 (< 0.25 dS/m) to 5 (> 5 dS/m). Salinity and TDS are computed by the instrument from EC.

Table 3: Descriptive statistics of EC and pH and paired comparison of the two campaigns (Wilcoxon signed-rank test)

Parameter (group)	January mean $\pm$ SD	January median (IQR)	April mean $\pm$ SD	April median (IQR)	Increase / decrease	p
EC, dS/m, all depressions (n = 20)	2.16 $\pm$ 1.52	1.82 (1.23–3.19)	4.36 $\pm$ 5.43	1.77 (0.52–6.08)	12 / 8	0.105
EC, dS/m, Bandé (n = 12)	2.71 $\pm$ 1.70	2.80 (1.44–3.90)	6.53 $\pm$ 6.14	5.56 (1.40–10.95)	10 / 2	0.012
EC, dS/m, Kwaya (n = 4)	0.85 $\pm$ 0.68	0.94 (0.40–1.40)	0.42 $\pm$ 0.26	0.48 (0.36–0.54)	0 / 4	0.125
EC, dS/m, Dungass (n = 4)	1.80 $\pm$ 0.11	1.82 (1.75–1.87)	1.82 $\pm$ 0.85	1.67 (1.36–2.12)	2 / 2	1.00
pH, all depressions (n = 20)	7.76 $\pm$ 0.60	7.66 (7.35–8.03)	8.51 $\pm$ 0.87	8.52 (7.91–9.24)	18 / 2	< 0.001
pH, Bandé (n = 12)	8.01 $\pm$ 0.66	7.95 (7.67–8.23)	8.81 $\pm$ 0.82	8.85 (8.18–9.56)	12 / 0	< 0.001
pH, Kwaya (n = 4)	7.32 $\pm$ 0.13	7.32 (7.26–7.38)	7.39 $\pm$ 0.49	7.37 (7.07–7.69)	2 / 2	0.88
pH, Dungass (n = 4)	7.45 $\pm$ 0.14	7.40 (7.37–7.49)	8.71 $\pm$ 0.18	8.68 (8.62–8.77)	4 / 0	0.125

Source: in situ measurements, Moussa Hassan S., 2026. SD: standard deviation; IQR: interquartile range (25th–75th percentiles); p: two-sided exact Wilcoxon signed-rank test. With n = 4, the smallest attainable p is 0.125, so no test can be significant in Kwaya or Dungass.

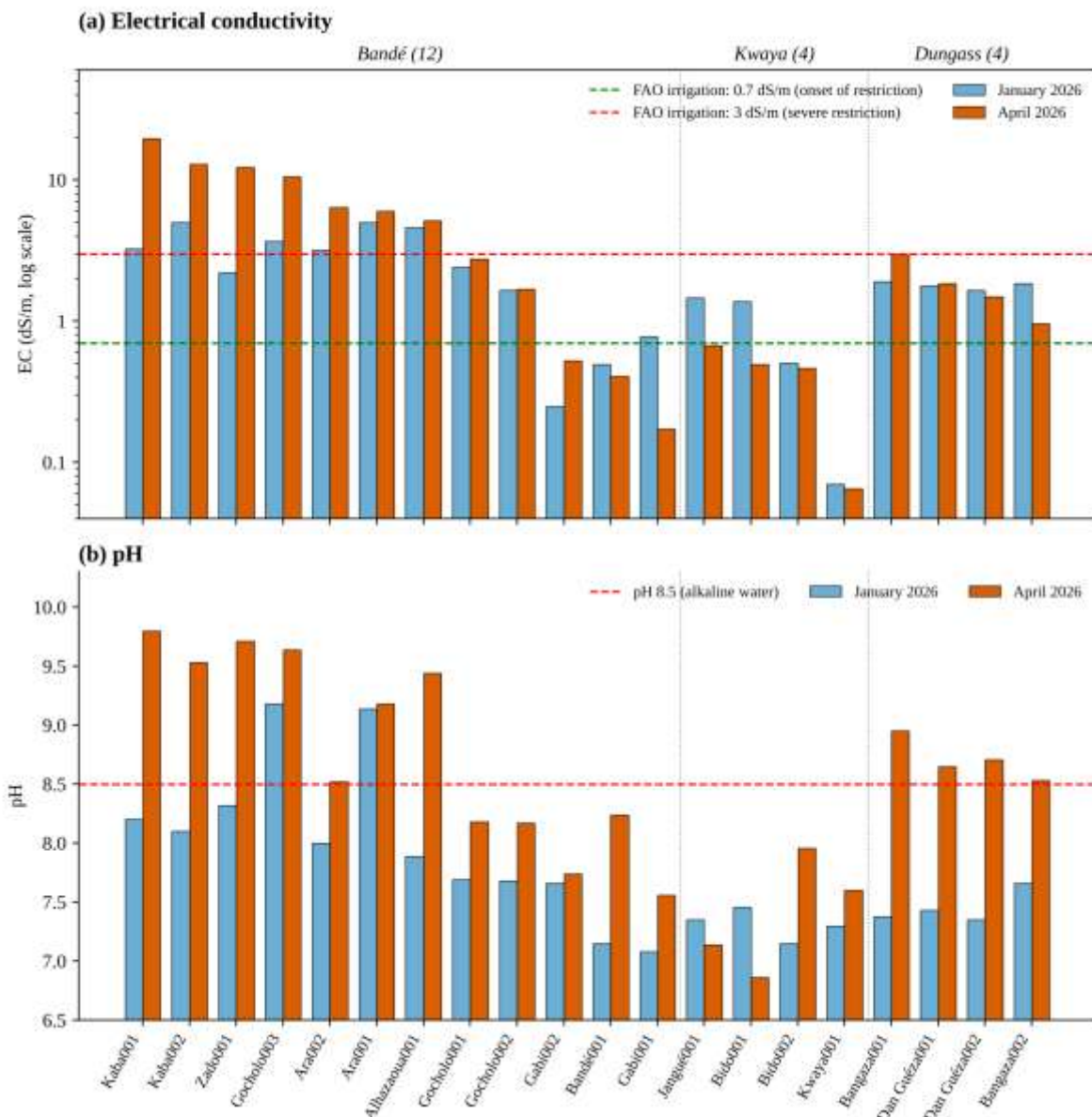


Figure 4: Electrical conductivity (a, logarithmic scale) and pH (b) of the 20 depressions in January and April 2026, compared with the FAO irrigation thresholds and with pH 8.5

Source: in situ measurements, Moussa Hassan S., 2026

Electrical conductivity and salinity:-

The increase is concentrated in Bandé (Figure 4a), where EC rises in 10 of the 12 depressions and the seasonal difference is significant ($p = 0.012$; median from 2.80 to 5.56 dS/m). EC more than doubles in six depressions, all in Bandé: Kaba001 ($\times 6.0$), Zado001 ($\times 5.6$), Gocholo003 ($\times 2.9$), Kaba002 ($\times 2.6$), Gabi002 ($\times 2.1$) and Ara002 ($\times 2.0$). At Kaba001, it rises from 3.27 dS/m in January to 19.6 dS/m in April. Values above 10 dS/m are also measured in April at Kaba002 (12.94 dS/m), Zado001 (12.23 dS/m) and Gocholo003 (10.52 dS/m). Conversely, EC decreases in the four depressions of Kwaya, in two depressions of Dungass and in two of Bandé (Bandé001 and Gabi001); where it decreases, an inflow of less mineralized water, for instance from the aquifer, is possible but was not measured. Salinity, derived from EC, follows the same pattern and reaches 1.13‰ at Kaba001 in April.

Differences between communes:-

The three communes differ clearly (Table 3). In Bandé, EC ranges from 0.25 to 5.01 dS/m in January (median 2.80 dS/m) and reaches a median of 5.56 dS/m in April; Bandé001 and the two Gabi depressions remain weakly

mineralized. In Dungass, the four depressions sampled are moderately mineralized (1.65–1.90 dS/m in January) and change little (median 1.67 dS/m in April); only Bangaza001 rises, to 2.97 dS/m. In Kwaya, EC is low (0.07–1.46 dS/m in January) and decreases in all four depressions. The difference between communes is at the limit of significance in January (Kruskal–Wallis, $p = 0.06$) and significant in April ($p = 0.048$), but with four depressions in Kwaya and four in Dungass, this test has low power and is given as an indication only.

Hydrogen potential (pH):-

pH increases in 18 of the 20 depressions between January and April (Figure 4b), from a median of 7.66 (IQR 7.35–8.03) to 8.52 (IQR 7.91–9.24); this is the only change that is significant over the whole network ($p < 0.001$). In April, pH exceeds 8.5 in 11 depressions, against 2 in January, and exceeds 9 in six, all in Bandé, with the highest values at Kaba001 (9.80) and Zado001 (9.71). It also rises in all four depressions of Dungass (from 7.45 to 8.71 on average), although EC changes little there; only two depressions of Kwaya (Jangué001 and Bido001) show a decrease. Across depressions, April pH increases with EC (Spearman's $\rho = 0.86$, $p < 0.001$). These values indicate alkaline water, probably loaded with sodium carbonates and bicarbonates; a pH of this order reduces the availability of some nutrients to plants. A pH above 8.5 is not sufficient, however, to establish a sodicity hazard, which depends on the sodium adsorption ratio (SAR), not measured here.

Suitability of water for agricultural and pastoral uses:-

Table 4 gives the number of depressions in each class of the use-based standards. For irrigation, six depressions fall under severe restriction in January and seven in April; over the same period, the number of depressions without restriction rises from four to seven, because EC decreases in several depressions. In April, seven depressions, all in Bandé, are in USSSL class C5 (> 5 dS/m). For livestock watering, the water remains excellent or very satisfactory in 13 depressions in April; it is no longer suitable for poultry in three, its use is limited or very limited in three others (Gocholo003, Kaba002 and Zado001), and it is no longer recommended at Kaba001.

Table 4: Number of depressions in each class of the use-based standards, January and April 2026 (20 depressions)

Standard	Class (EC, dS/m)	January 2026	April 2026
USSSL, salinity hazard	C1 (< 0.25)	1	2
	C2 (0.25–0.75)	3	5
	C3 (0.75–2.25)	9	4
	C4 (2.25–5)	5	2
	C5 (> 5)	2	7
FAO, irrigation	No restriction (< 0.7)	4	7
	Slight to moderate restriction (0.7–3)	10	6
	Severe restriction (> 3)	6	7
FAO, livestock watering	Excellent (< 1.5)	7	9
	Very satisfactory (1.5–5)	11	4
	Satisfactory, unfit for poultry (5–8)	2	3
	Limited to very limited use (8–16)	0	3
	Not recommended (> 16)	0	1

Source: in situ measurements, Moussa Hassan S., 2026; classification after Richards (1954) and Ayers & Westcot (1985). The USSSL classification is incomplete without SAR.

Salinization risk index by depression:-

The mean SRI rises only slightly, from 3.20 in January to 3.35 in April ($p = 0.45$), but the distribution of levels changes markedly (Figures 5 and 6): the number of depressions at the critical level rises from two to seven, while the number at the low level rises from four to seven. The maps locate the most saline depressions; they do not describe salinity in the areas between the depressions measured.

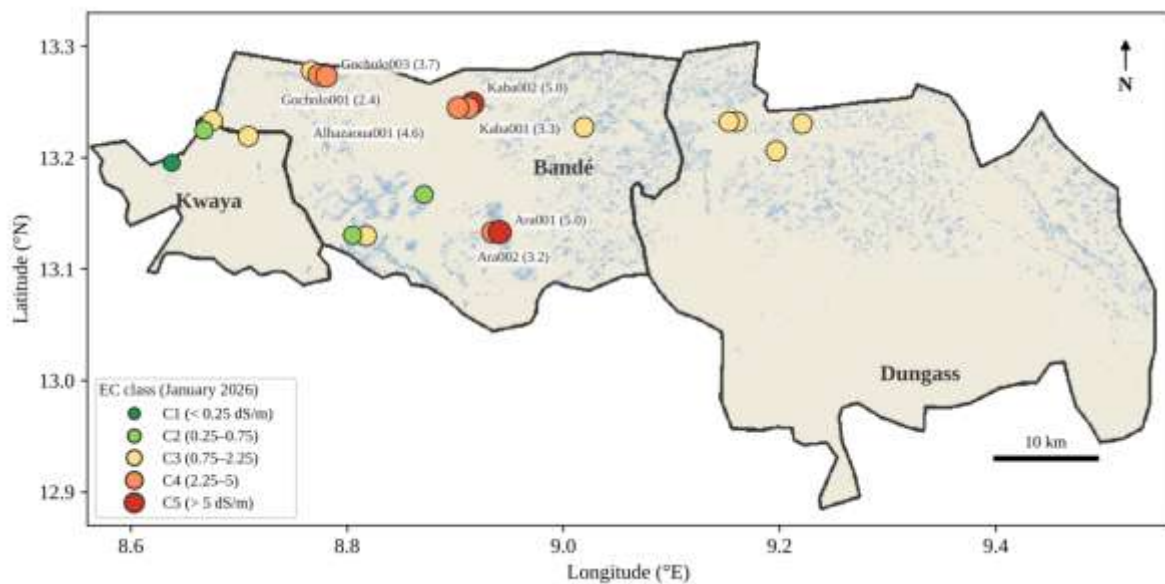


Figure 5: Salinization risk index (USSL EC class) by depression, January 2026

Point symbols, without interpolation; value in brackets: EC (dS/m). Background: study area and 2025 depressions (Sentinel-1/2); in situ measurements, Moussa Hassan S., 2026

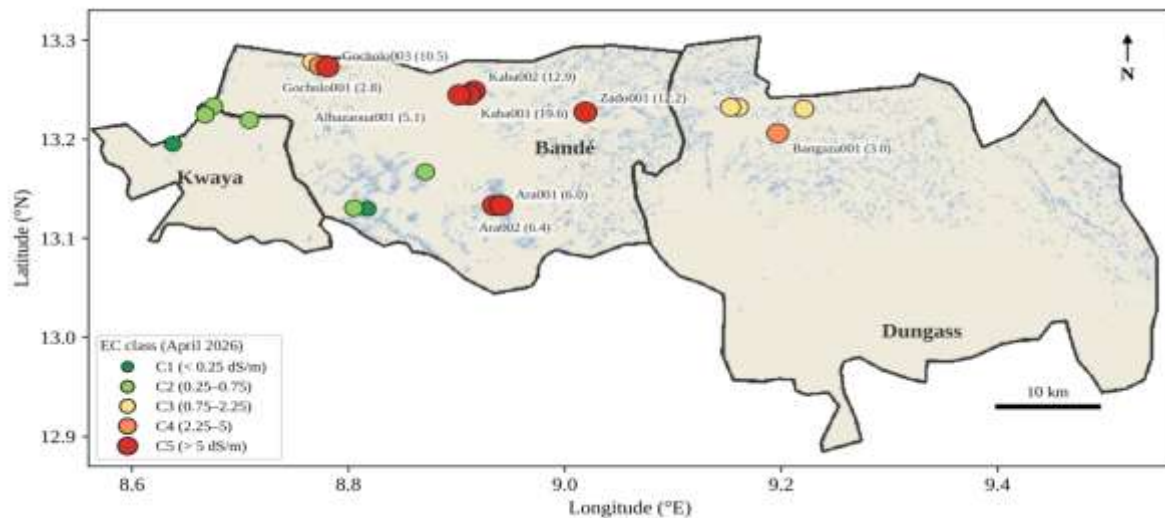


Figure 6: Salinization risk index (USSL EC class) by depression, April 2026

Point symbols, without interpolation; value in brackets: EC (dS/m). Background: study area and 2025 depressions (Sentinel-1/2); in situ measurements, Moussa Hassan S., 2026

The maps show three distinct situations. In Bandé, the risk is contrasted and changes rapidly: in April, 7 of the 12 depressions are at the critical level, and five of them have more than doubled their EC since January (Kaba001, Zado001, Gocholo003, Kaba002 and Ara002). This is where the seasonal deterioration is concentrated; in the field, it is visible as salt efflorescences fringing the depressions (Figure 7). In Dungass, the four depressions sampled remain at the moderate level (class C3) in both campaigns, except Bangaza001, which moves to the high level in April; all four are located in the west of the commune, and nothing allows this finding to be extended to the rest of Dungass. In Kwaya, the risk is low and decreases between January and April, whereas residents describe a recent appearance of salinity: this gap between perception and measurement calls for monitoring.



Figure 7: Salt crystallization around a depression at Kaba (Bandé commune)

Photograph: Moussa Hassan S., December 2024

Comparison with groundwater:-

The piezometric records show that the aquifer lies close to the surface. In the study area, the median depth to water ranges from 0.85 m (Angoual Manda) to 5.07 m (Baykori) and is less than 2.6 m in 8 of the 12 piezometers, with a difference of 0.5 m at most between the dry season and the end of the rainy season. Between 2014 and 2023, the water table rises significantly in 4 of the 12 piezometers, by 0.9 to 2.0 m per decade (Ara Haoussa, Baykori, Gourgouzou 3 and Angoual Manda; Mann–Kendall test, $p < 0.01$), falls in two (Dan Tekey and Dan Dilla) and shows no significant trend in the other six. Longer series show a significant rise of 0.4 to 1.1 m per decade since 2005 at Gourgouzou 3, Kan Dawa Oukou and May Gwaiba ($p < 0.001$).

Groundwater is weakly mineralized (Figure 8). In the study area, its median EC is 0.12 dS/m over 210 measurements; only two measurements exceed 0.7 dS/m, and none reaches 3 dS/m. More mineralized water is found to the north, near the Korama channel, where the median EC of the Gomba, Koukourey and Ruwan Chabara piezometers ranges from 0.97 to 1.36 dS/m (maximum 2.21 dS/m at Gomba). Groundwater pH is close to neutrality (median 6.6). The median EC of the depressions is thus about 15 times that of groundwater in both campaigns, and the maximum (19.6 dS/m at Kaba001) about 160 times.

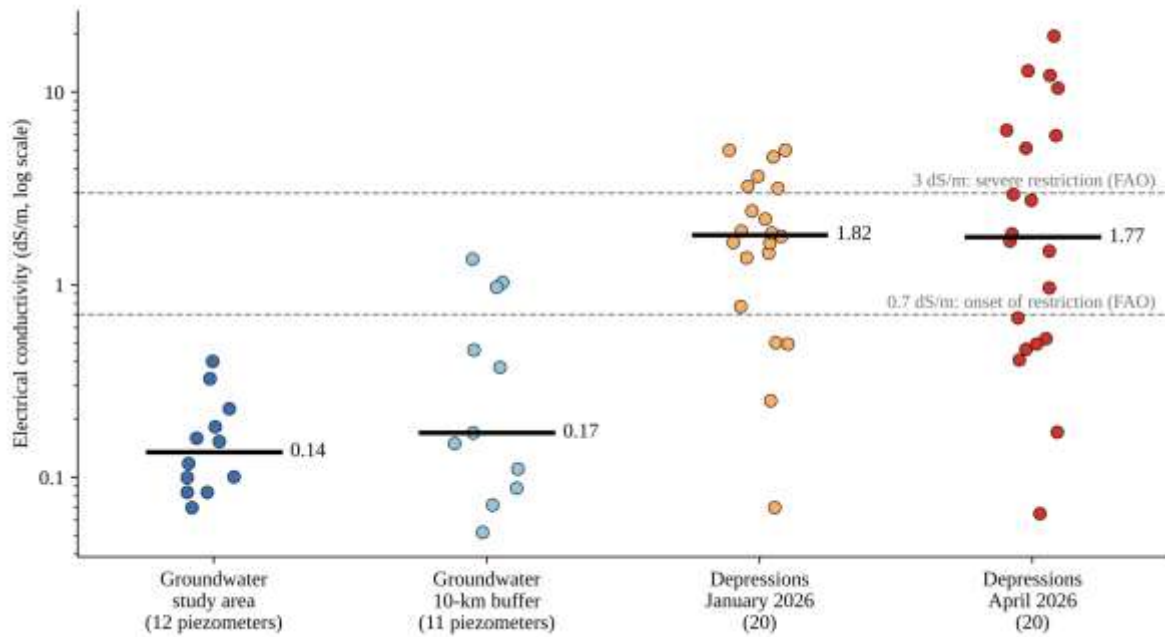


Figure 8: Electrical conductivity of groundwater (median 2015–2022 per piezometer) and of depression water (January and April 2026), compared with the FAO irrigation thresholds

Logarithmic scale; points: piezometers or depressions; bars: median. Sources: DRH Zinder (2026); in situ measurements, Moussa Hassan S., 2026

Discussion:-

Observed patterns and inferred mechanisms:-

The measurements establish three facts. First, mineralization varies widely between depressions, from fresh water at Kwaya001 to very saline water at Kaba001. Second, the dry season does not raise EC uniformly: EC increases in 12 of the 20 depressions, significantly so in Bandé only, and decreases in the four depressions of Kwaya, whereas pH increases almost everywhere. Third, depression water is an order of magnitude more mineralized than the shallow, weakly mineralized and near-neutral groundwater measured in the piezometers of the area. The mechanisms that explain these facts are inferred, not measured. The rise in EC where depressions shrink is consistent with evaporative concentration, the central mechanism of salinization in arid and semi-arid environments (Shokri et al., 2024), but water volumes were not monitored. The case of Kaba001 (19.6 dS/m; pH 9.8) resembles observations in arid endorheic basins such as the Barkol Basin in China, where salinity increases towards internal terminal sinks as a result of mineral dissolution and evapotranspiration (Wang et al., 2025). The comparison with groundwater supports, without proving, a surface origin of most of the salt load. The median EC of the depressions (1.82 dS/m in January) is about 15 times that of the aquifer in the study area (0.12 dS/m). The same contrast is observed regionally: the mean EC of the phreatic aquifer is only 132 $\mu\text{S}/\text{cm}$ in the upper Korama basin (Souleymane et al., 2020a) and does not exceed 325 $\mu\text{S}/\text{cm}$ in the alluvial aquifer of the Goulbi N’Kaba (Yahouza et al., 2018). Although groundwater may locally be more mineralized beneath the depressions, where no piezometer is installed, this order-of-magnitude difference indicates that most of the salt load is acquired at the surface, in shallow water bodies fed by groundwater and subject to intense evaporation. The evaporation signature identified in recharge waters of the basin by Sandao et al. (2018) is consistent with this interpretation. An order of magnitude helps to read this gap: raising EC from 0.12 to 19.6 dS/m by evaporation alone would require a concentration factor of about 160, that is, the evaporation of more than 99% of the water entering the depression. Such a concentration cannot occur in a single dry season; it implies an accumulation of salts over several years in depressions without outlet, which the rains flush only partly. A salt mass balance (water volume, EC and duration of flooding for each depression) would make it possible to test this hypothesis.

Origin of salts: hypotheses and comparison with the depressions of Gouré and the Manga:-

The bulk parameters measured here are not sufficient to establish the origin of the salts. Residents attribute it to the dissolution of salt-bearing rocks by the rising water, and this hypothesis guided the initial design of the study. It cannot be verified with the available data, in the absence of major-ion analyses and of geological data on the Continental Terminal beneath the depressions. Studies on waters of the Zinder region and on the Korama aquifers have shown that groundwater mineralization varies widely depending on the formations crossed and on water residence time (Amadou et al., 2014; Issa et al., 2015; Souley Moussa et al., 2018), but the piezometers of the study area indicate weakly mineralized groundwater. Local dissolution of saline horizons beneath the lowlands therefore cannot be excluded, but it is not required to explain the observed values.

The Manga depressions, in the department of Gouré, are organized in a similar way. Ambouta et al. (2018) describe mineralization increasing from the margins towards the centre of the depressions, a sodium bicarbonate facies at Iskour, and a recent infill capped by evaporites. The natron that crystallizes there as crusts during the dry season, in depressions with a shallow water table (Illou, 2018), is a sodium carbonate; in the Kowar, natron-pan salts are dominated by trona (Malam Moussa et al., 2022). The pH above 9 measured in April in six depressions of Bandé and the exploitation of natron in the most saline depressions probably reflect the same evolution towards sodium carbonate waters. Groundwater in the Manga, however, remains close to neutral (pH 6.2–7.4; Ambouta et al., 2018), as does that of the study area (median pH 6.6), which places alkalization in evaporating surface waters rather than in the aquifer. Finally, the accumulation of salts towards the low points where water resides longest, described in the Goulbi N’Kaba valley (Yahouza et al., 2018) and in the Manga depressions (Ambouta et al., 2018), is consistent with the saline fringes observed around the depressions; the 20 depressions measured are, however, too few to establish a regional gradient, and the most saline ones lie in the centre of the study area (Bandé), not at its lowest point (Dungass).

These observations suggest a self-reinforcing process, which remains a hypothesis. The return of water expands the flooded areas and lengthens the periods of stagnation, which increases the amount of salt concentrated by evaporation in the lowlands. In the field, salinization is associated with the die-off of woody vegetation around several depressions, which may in turn increase runoff towards them. Descroix et al. (2015, 2018) had already called for looking beyond climatic factors alone and integrating these pedological and anthropogenic feedbacks into the study of hydrological hazards in the Sahel. In the Korama, flooding and salinization appear to stem from the same water dynamics and should be managed jointly.

Implications for irrigation, crops, livestock and rural water resources:-

For irrigation, seven depressions exceed 3 dS/m in April, the threshold of severe restriction (Ayers & Westcot, 1985). The short-cycle crops most grown around the depressions are sensitive to salinity: full yield requires an irrigation water EC below 0.8 dS/m for onion, 0.9 dS/m for lettuce and 1.7 dS/m for tomato, and yield falls by about 10% above 1.2, 1.4 and 2.3 dS/m respectively (Ayers & Westcot, 1985). In April, the 10% yield-loss thresholds are exceeded in 12 depressions for onion and lettuce and in 9 for tomato, and the median EC of the network (1.77 dS/m) already exceeds the full-yield thresholds of all three crops. Irrigating with C4–C5 water also leads to salt accumulation in the root zone unless an adequate leaching fraction and efficient drainage are ensured (Richards, 1954), which is difficult in closed lowlands with a shallow water table. pH values above 9 further reduce the availability of nutrients such as phosphorus, iron and zinc; the sodicity hazard, which would call for calcium amendments such as gypsum, can only be assessed once SAR has been measured. For livestock, the water of most depressions remains usable, but in April four depressions are of limited use or not recommended, and three are unsuitable for poultry (Ayers & Westcot, 1985), at the time when other water points are drying up. For domestic use, the WHO sets no health-based guideline value for TDS but notes that palatability deteriorates markedly above about 1 g/L (WHO, 2017), which corresponds to an EC of about 1.5 dS/m with the usual conversion factor of 640 mg/L per dS/m (Ayers & Westcot, 1985); in April, 11 of the 20 depressions exceed this level. The weakly mineralized aquifer (median 0.12 dS/m) is therefore the best alternative source for domestic use and for irrigation in the most saline sectors, subject to its sanitary quality (Souleymane et al., 2022, 2024). Farmers have already drawn this conclusion: for market gardening, they prefer to dig wells or boreholes near the depressions rather than irrigate with depression water.

Management implications:-

The three situations call for different responses. In Bandé, the risk depends strongly on season, and the timing of water use matters: market gardening and irrigation should preferably be carried out early in the dry season, before concentration becomes critical, and in April the most saline depressions should be reserved for salt-tolerant crops or

replaced by groundwater for irrigation. The difficulty is that peak salinity coincides with the period when market gardening most needs water. In Dungass, where mineralization is moderate and stable in the depressions measured, the priority is to extend monitoring towards the east of the commune and to reduce household vulnerability. In Kwaya, regular EC monitoring would make it possible to act before soils are affected. Earlier studies in Niger give some guidance here. In the Kollo irrigation scheme, controlled leaching removed 19–39% of the salt stock from the upper 40 cm of soil (Issifou Adam, 2011), but this practice requires low-salinity irrigation water, which the most saline depressions no longer provide in April; the weakly mineralized groundwater of the basin (Souleymane et al., 2020a) could fulfil this role, subject to its sanitary quality (Souleymane et al., 2024). The efflorescences observed at Kaba would warrant mineralogical characterization, as carried out at Kollo (Ducloux et al., 1994), to distinguish neutral salts from sodium carbonates, which pose different hazards to soils. Finally, in the Manga, salinity is already among the constraints cited by 19–28% of farmers depending on the type of depression (Malam Assane et al., 2021): the perceptions collected in the Korama in 2024 suggest that the southern strip is following the same trajectory.

Scope and limitations of the approach:-

In situ measurement is inexpensive and easily repeatable in remote areas, from which transporting samples to a laboratory is difficult. The SRI relies on a single parameter and standard thresholds; it is simpler than a multi-criteria analysis but remains usable with the available resources. The approach nevertheless has limitations. A portable instrument provides approximate values rather than laboratory measurements: its EC accuracy is $\pm 2\%$ of full scale, and EC was measured with the factory calibration. TDS and salinity are derived from EC and add no independent information. Two campaigns do not cover the full annual cycle, and water volumes were not monitored, so evaporative concentration is inferred rather than demonstrated. Without analysis of major ions (sodium, calcium, magnesium, chloride, sulfate, bicarbonate), neither can the SAR be calculated nor the hydrochemical facies determined, as Souleymane et al. (2020a) did for the upper-basin aquifer. The 21 depressions were selected purposively among water bodies used for market gardening and are not representative of all depressions; only four were sampled in each of Kwaya and Dungass, which limits comparisons between communes and precludes spatial interpolation. Finally, no piezometer is located in a depression, so exchanges between groundwater and surface water are inferred from nearby piezometers.

Conclusion:-

In situ physico-chemical measurements in 21 depressions of the southern Korama strip, 20 of which were measured in both campaigns, were used to describe water salinity and to derive a salinization risk index for each depression. Mineralization varies widely between depressions, from 0.07 to 19.6 dS/m. Between the beginning and the end of the dry season, pH increases significantly in almost all depressions, whereas EC increases in 12 depressions only, significantly so in Bandé: mean EC doubles, but the median does not change. In April, seven depressions entail severe restrictions for irrigation, and four are of limited use or not recommended for livestock watering. The risk takes three forms: contrasted and seasonal in Bandé, moderate and stable in the four depressions sampled in Dungass, and low in Kwaya, where residents nevertheless perceive a recent salinity. Depression water is an order of magnitude more mineralized than the shallow, weakly mineralized groundwater, which points to the concentration of salts by evaporation in closed depressions fed by the rising aquifer; the dissolution of salt-bearing formations of the Continental Terminal remains a hypothesis to be tested. Regular monitoring of depression water quality is now needed, complemented by major-ion, SAR and soil analyses and by a salt mass balance of the most saline depressions, with interventions tailored to whether the risk is seasonal or stable.

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Ethics statement:-

The measurements presented concern surface waters only. Residents' perceptions cited in the Introduction come from a household survey conducted in 2024 among 293 households; no personal data are published. Research authorization was obtained from André Salifou University of Zinder and from the communes of the study area, and the consent of each respondent was obtained before the questionnaire was administered.

Appendix:-**Table A1: Location of the 21 depressions sampled (WGS 84, decimal degrees)**

Depression	Commune	Latitude (°N)	Longitude (°E)	Campaigns
Kaba001	Bandé	13.24782	8.91343	Jan. + Apr.
Kaba002	Bandé	13.24820	8.91318	Jan. + Apr.
Zado001	Bandé	13.22787	9.01730	Jan. + Apr.
Gocholo003	Bandé	13.27453	8.78006	Jan. + Apr.
Ara002	Bandé	13.13283	8.93600	Jan. + Apr.
Ara001	Bandé	13.13460	8.93797	Jan. + Apr.
Alhazaoua001	Bandé	13.24587	8.90157	Jan. + Apr.
Gocholo001	Bandé	13.27717	8.76934	Jan. + Apr.
Gocholo002	Bandé	13.27779	8.76999	Jan. + Apr.
Gabi002	Bandé	13.13061	8.80412	Jan. + Apr.
Bandé001	Bandé	13.16748	8.87035	Jan. + Apr.
Gabi001	Bandé	13.13027	8.81697	Jan. + Apr.
Jangué001	Kwaya	13.22048	8.70821	Jan. + Apr.
Bido001	Kwaya	13.22971	8.66548	Jan. + Apr.
Bido002	Kwaya	13.23484	8.67327	Jan. + Apr.
Kwaya001	Kwaya	13.19652	8.63740	Jan. + Apr.
Bangaza001	Dungass	13.20745	9.19530	Jan. + Apr.
Dan Guéza001	Dungass	13.23395	9.15593	Jan. + Apr.
Dan Guéza002	Dungass	13.23295	9.15452	Jan. + Apr.
Bangaza002	Dungass	13.23195	9.21917	Jan. + Apr.
Zado002	Bandé	13.22862	9.01775	Incomplete (excluded)

Source: field GPS surveys, Moussa Hassan S., 2026

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