https://doi.org/10.17221/37/2024-SWR

Assessment of soil salinity and environmental factors in the Kesem irrigation scheme, Afar Region, Ethiopia

Mengistu Jiru[1], Boja Mekonnen[1], Henk Ritzema[2], Fentaw Abregaz[3]*

[1]*Department of Water Resources Engineering, School of Civil Engineering and Architecture Adama Science and Technology University, Adama, Ethiopia*
[2]*Water Resources Management Group, Wageningen University & Research, Wageningen, The Netherlands*
[3]*Agricultural Water Management Research, Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia*

**Corresponding author: mengistubosie@gmail.com*

Citation: Jiru M., Mekonnen B., Ritzema H., Abregaz F. (2024): Assessment of soil salinity and environmental factors in the Kesem irrigation scheme, Afar Region, Ethiopia. Soil & Water Res., 19: 191–199.

Abstract: Soil salinity is a growing problem for agricultural production in irrigated areas of arid and semi-arid regions. The extent of salinity levels has not been fully studied in the Kesem irrigation scheme in Ethiopia's Afar region. The objective of the study was to identify the main issues related to soil salinity and their variations and to assess the influence of environmental variables on soil salinity using multivariate analysis (MVA). The dominant cations in the soil were found to be soluble Na^+, Ca^{2+} and K^+ while SO_4^{2-} and Cl^- were the dominant anions. These ions are responsible for the salinity in the scheme. Groundwater table surveys showed that cultivated fields experienced greater fluctuations in groundwater levels compared to abandoned land due to frequent irrigation. The first two principal components explained approximately 60% and 63% of the total variation in salinity for the top and bottom layers, respectively. The difference between the top and bottom layers suggests a management influence. According to redundancy analysis, the groundwater depth and length of irrigation years were identified as the major environmental factors contributing to 99% and 52% of the variability in salinity, respectively. These findings highlight the importance of considering the rising groundwater levels in future land management decisions.

Keywords: anions; cations; environmental variables; groundwater levels; multivariate analysis

One of the main barriers to agricultural production is the prevalence of the salt problem in arid and semi-arid regions. Salt damage has been reported on more than 11 million hectares of Ethiopian land (Taddesse 2001; Ruff et al. 2007), leading to a complete loss of land value by being abandoned for crop cultivation as experienced in the Awash River Basin in the Rift Valley. In the middle Awash River Basin, one of the new development areas for sugarcane production is the Kesem irrigation scheme.

Except in a few fields, no comprehensive investigation was yet conducted to identify conclusive evidence for causes of soil salinity and its variability in the Kesem area in the middle Awash River Basin. The extent to which salinity levels have changed over time after the introduction of irrigation has not been fully studied to date. This is because rigorous investigations of soil property distributions are rare, and statistical methodologies for soil survey applications are not commonly utilized (Momtaz et al. 2009). Although classical statistical analysis attempts to describe the distribution of a measurable property and determine the reliability of a sample drawn from a population, they typically fail to explain important

https://doi.org/10.17221/37/2024-SWR

cause-and-effect relationships between multiple variables. Moreover, soil chemical variables are affected by multiple factors, and different variables have different responses to these factors, causing complicated multivariate relationships between them (Zhang et al. 2008, 2020). Oftentimes, these data are also interrelated, and appropriate statistical methods are needed to fully answer the questions of multiple variables or observation studies. Various researchers have been using multivariate analysis techniques to simplify the issue of the complex nature of soil quality data assessment.

Multivariate analysis (MVA) is a very useful technique in soil research because it can simplify multivariate datasets without a substantial loss of information (Johansson & Stenberg 2000). It allows for handling highly collinear variables, as is often the case in soil studies and accounting for the effects of environmental factors. Multivariate analysis techniques, mainly principal component analysis (PCA), redundancy discriminant analysis (RDA) and cluster analysis (CA), have been widely used in soil survey and research (Webster & Oliver 1990).

The three analysis methods have always been used in the study of soil ionic composition (Aguilera et al. 2011). A combined analysis of the MVA tools has not yet been performed in soil research in the irrigated schemes of the Awash River basin in Ethiopia and has proven to be very effective in studying soil salinity. The viability of this combined analysis method in a large irrigation scheme has not been verified. To better manage basin salinity issues, a characterization of the current salt composition and the key environmental constraints that may affect this issue is urgently needed. Therefore, the aim of this study was to characterize soil-soluble salts in the Kesem irrigation scheme and to describe the relationship between these salt ions and environmental factors, including groundwater table, distance from the nearest water body, and length of irrigation using the technique of MVA.

MATERIAL AND METHODS

Study area. The study was conducted in the irrigated Scheme of Kesem, located in the middle Awash River Basin (Figure 1) in the Afar region of Ethiopia, between 9°7'N and 9°12'N, and 39°57'E and 40°5'E at about 750 to 850 m a.s.l., the area experiences a typically tropical semi-arid and arid climate with annual rainfall normally in the range 350 to 600 mm (mean = 470 mm). Annual potential evapotranspiration, estimated by the Penman method, approximates 2 400 mm, ranging from a monthly mean of 170 mm in August to 252 mm in June. The Kesem River forms its northern border, while the Deho swamp forms its southern and eastern boundaries. The total surface area of the irrigation scheme is 50 km^2 or 5 000 ha. Kesem irrigation scheme employs a furrow irrigation system. This method involves the use of furrows with blocked ends, which can vary in length, though the most common lengths are 100 and 200 m.

Most of the soils are predominantly medium textured: typically silty loams, silty clay loam, very fine sandy loam and very fine sandy clay loams, with potentially moderate to high water holding capacities (MacDonald & Partners 1987). The main part of the state farm, in the western part, is an old scheme that has been extended over the decades. It was started in 1905 by a Frenchman whose name is Saboret.

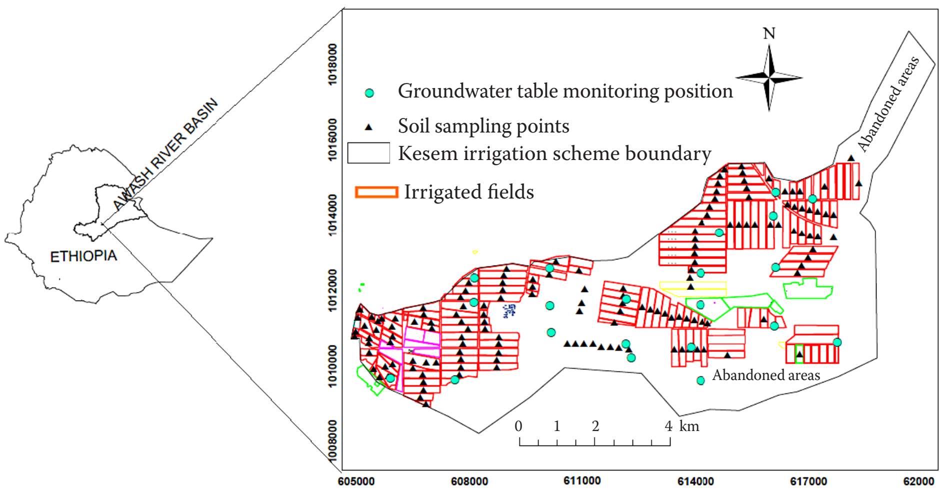

Figure 1. Map of the study area

https://doi.org/10.17221/37/2024-SWR

Since 2007, it has been part of the Kesem irrigation expansion project. Some areas of the project were initially affected by problems of salinity and/or sodicity. Most of the abandoned area in the scheme has been covered with an exotic plant called *Prosopis juliflora*, reported as the only fast-growing fuel wood capable of growing in a wide range of soils, including problematic sites like degraded lands, salt-affected soils and waterlogged areas (Basavaraja et al. 2007).

Groundwater table dynamics investigations. On a grid of almost 1 by 2 km, 20 monitoring locations for the groundwater table (GWT) at the study site were selected (Figure 1). Using a hand auger of 100 mm diameter, various depths were bored at selected spots up to the water table's limit. Then, a prepared 63 mm diameter pipe was carefully placed inside each excavated pit. The depth of the water table was determined by lowering the measuring stick in the pipe (piezometer).

Soil sampling and laboratory analysis. Sampling was carried out from February 2021 to October 2021. February, March, June, and October had very low rainfall, around 0–20.5 mm. While, April, May, August, and September had relatively higher rainfall, ranging from 62.2 to 187.6 mm. On the other hand, evapotranspiration (ET) was consistently high, ranging from 160 to 231 mm monthly during soil sampling and groundwater monitoring. There are active cane and abandoned fields in the south block of Kesem scheme due to salinity. A field in the scheme is mostly rectangular in shape and its size ranges from just 1.5 to 30 ha. A total of 308 composite soil samples were taken from each field unit systematically at the depths of 0–30 and 30–60 cm of topsoil. The intensive data set of salinity by depth and location can also be used to assess the adequacy of past leaching/drainage practices (Rhoades 1992). Five auger sites were obtained in a cross (X-shape) pattern to create one composite sample. The sampling sites were uniformly distributed and had good coverage of the study area, except for some individual areas conditioned by their limited accessibility.

The soil samples were air-dried, grinded using a standard soil sample grinding machine and allowed to pass through a 2 mm sieve.

A soil-water suspension with a ratio of 1 : 5 was prepared following the methods described in Gupta (2004). All samples were analysed for soluble cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and soluble anions (Cl^-, CO_3^{2-}, HCO_3^- and SO_4^{2-}) were determined from suspensions of 1 : 5 soil water ratio. At the same time, soil pH was measured using a digital pH meter and electrical conductivity (EC) by a digital conductivity meter according to the method outlined by Richards (1954) and Rhoades et al. (1999), respectively. The value of the salt concentration of each sample (EC 1 : 5 reading) was converted to saturation paste extract (ECe) by multiplying it with the conversion factor as suggested by Yarima (1993).

Water soluble cations (Ca^{2+} and Mg^{2+}) were measured by ethylene diamine tetra acetic acid (ETDA) (Gupta 2004), while K^+ and Na^+ were measured by flame photometer (FAO 1984).

Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations were determined by simple acidimetric titration using phenolphthalein as an indicator for CO_3^{2-} (pH > 8.5) and methyl orange for HCO_3^- (pH < 6), respectively (Hesse 1971). Subsequently, chloride (Cl^-) was determined by titrating the aliquot used for CO_3^{2-} and HCO_3^- determinations using silver nitrate to potassium chromate endpoint. Sulphate ion was determined gravimetrically by precipitating as barium sulphate as described by FAO (1984).

Statistical analyses. Descriptive statistical analysis was performed, calculating the mean, median, maximum, and minimum, and standard deviation, coefficient of variation, skewness, and kurtosis. The presence of outliers was checked and removed in the Excel spreadsheet. The Kolmogorov-Smirnov normality test was also performed to check the normality of the data set and whether the dataset is distributed to conform to a normal distribution (R Core Team 2022).

A Pearson's correlation analysis was then performed to assess the relationships and associations between variables (Makowski et al. 2020). A multivariate gradient analysis combining ordination and multiple regression techniques was performed to integrate the information on spatial variability and relationships between soil salinity and environmental factors. The ordination is aimed at finding canonical axes that explain the maximum variability in the chemical properties of the samples. Unconstrained ordination (i.e., indirect gradient analysis) looks for the variables that might best explain the composition of the salt ions and takes them as axes of ordination. On the other hand, in constrained ordination (i.e. direct gradient analysis), the variability is limited to being explained only in terms of the environmental factors. The two approaches complement each other.

The former indirect method gives the main gradient of variability, while the latter direct involves only the variability associated with environmental

https://doi.org/10.17221/37/2024-SWR

factors. According to the gradient length analysis (Hill & Gauch 1980, cited in Zhang et al. 2020), which was previously performed on the response data set, a linear analysis model was selected, and thus, the two methods, PCA and RDA, were determined for the indirect and direct gradient analysis used. The PCA and RDA were conducted with R Studio (Ver. 4.2.1) (R Core Team 2022). Both PCA and RDA analyses were performed on the untransformed data, standardized and based on the correlation matrix. In the case of PCA, chemical variables were centred and standardized, while for RDA they were standardized by error variance. Besides, two different Monte Carlo permutation tests were performed to evaluate the signification of ordination axes, one for just the first axis and the other one for all canonical axes together (sum of canonical eigenvalues).

RESULTS AND DISCUSSION

Summary of soil ionic composition. A descriptive analysis of the soluble cation and anion composition in the top (0–30 cm) and bottom (30–60 cm) layers is included in Table S1 in Electronic Supplementary Material (ESM). The average pH of the soil in both the 0–30 cm and 30–60 cm layers was measured to be 8.23, with values ranging from 7.10 to 9.45. This pH range indicates that the soil is slightly alkaline, falling within the high (7.0–8.5) to very high (> 8.5) range as defined by Landon (1991). The study area revealed a significant variability in soil EC, indicating variations in the concentration of dissolved salts within the soil. In the top layer, EC values ranged from 0.24 to 10.12 dS/m, reflecting a wide range of salt concentrations. This suggests that certain areas within the upper layer may have higher salt content, leading to higher EC values. In contrast, the bottom layer exhibited a narrower range of EC values, ranging from 0.03 to 1.25 dS/m, indicating relatively lower salt concentrations.

Table 1. Characteristics of the first five principal components (PC) from the principal component analysis of the standardized values of ten soil variables

	PC1	PC2	PC3	PC4
0–30 cm (top layer)				
Eigenvalue (λ*i*)	4.35	1.70	1.12	0.84
Proportion of variance (%)	43.49	16.98	11.16	8.36
Cumulative variance (%)	43.49	60.48	71.64	80.00
30–60 cm (sub layer)				
Eigenvalue (λ*i*)	4.50	1.80	1.09	0.94
Proportion of variance (%)	44.99	18.04	10.93	9.44
Cumulative variance (%)	44.99	63.02	73.95	83.39

The average concentration of the major soluble cations in both layers shows a similar order from highest to lowest as follows: $Na^+ > Ca^{+2} > K^+ > Mg^{2+}$ (Table 1). Soluble anions also followed the same order as $SO_4^{2-} > Cl^- > HCO_3^- > CO_3^{2-}$ in both layers. In almost all areas, soluble Na^+, Ca^{2+} and K^+ dominated among the cations and SO_4^{2-} and Cl^- among the anions at specified depth. The carbonate and bicarbonate concentrations were nearly similar in both layers but low compared to Zhang et al. (2020) investigations and comparable to the result of Cui et al. (2019). This implies that the Na^+ and Ca^{2+} salts of SO_4^{2-} and Cl^- are the ions that cause the very high salinity in some parts of the area. In other studies (Visconti et al. 2009; Cui et al. 2019; Zhang et al. 2020), sodium, calcium and magnesium are the first three most abundant soluble cations in salt-affected soils.

The elevated EC observed in the topsoil layer can be attributed to a combination of factors. One primary factor is the presence of a high saline groundwater table (in abandoned fields) in a low-lying area characterized by an arid climate, where evapotranspiration (ET) exceeds precipitation for at least part of the year. Inadequate drainage (Zaman et al. 2018) within certain sections of the study area has also allowed for the accumulation of soluble salt ions.

In the top and bottom soil layers, there is a notable right skewness in the distribution of EC and the majority of anions and cations, except for pH, which exhibits a moderate skewness due to the occurrence of high values. This suggests that there is a build-up of significant ions in the surface soil, either through natural processes or human activities (Zhang et al. 2008). Additionally, the non-normal distribution of the raw data is evident from the observed asymmetry and the high kurtosis coefficients.

Groundwater level and flow direction. The results of the groundwater level monitoring show both temporal and spatial fluctuations. This study has shown that the mean piezometers' water levels can change over time in irrigated and abandoned fields, respectively, by 1.06 to 4.40 m and 0 to 4.38 m. Irrigated fields revealed more sporadic variations in groundwater levels than abandoned fields (Figure 2). This could be a result of the sugar cane fields receiving frequent irrigation. In arid and semi-arid regions where the (inevitable) inefficient use of sur-

https://doi.org/10.17221/37/2024-SWR

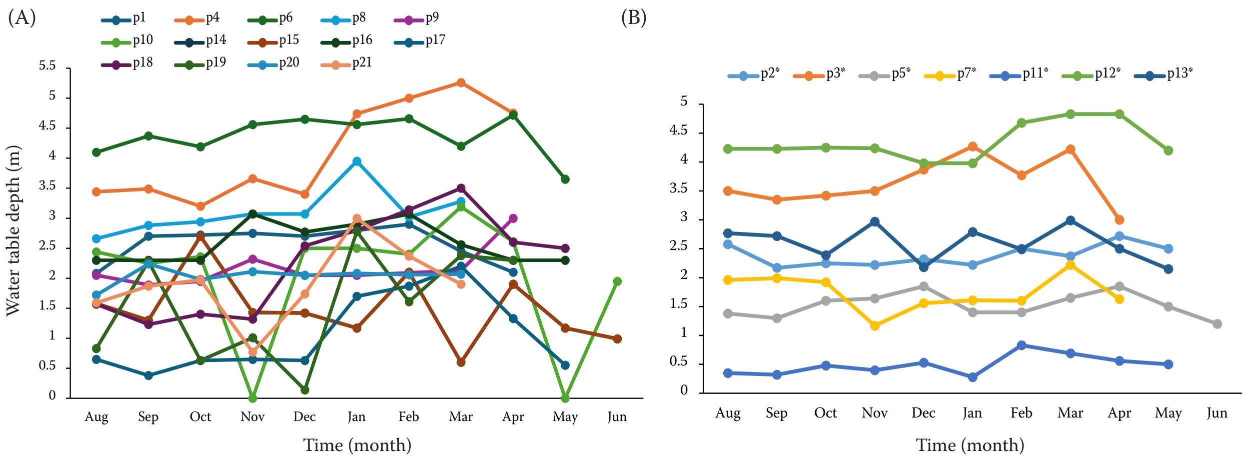

Figure 2. Groundwater table fluctuation in irrigated fields (A) and abandoned fields (B)
p – points of groundwater monitoring or piezometers

face irrigation water has caused groundwater rise and secondary salinization. Abandoned fields usually had a shallower water table than irrigated areas. As a result, one of the main contributors to the area's drainage problems (salinity and waterlogging) is the increase in groundwater in abandoned areas.

The water table is relatively deeper in the area's western and northern parts. Figure 3A shows a groundwater level contour map based on the piezometer reading on a static groundwater water level. The groundwater flow path is thought to proceed from the west and north to the east (the Awash River) and southeast (Figure 3B). It is considered the groundwater flows along the surface gradient /geography.

Correlation among soil ionic compositions. The results of the Pearson correlation analysis are presented in Figure 4. The strongest correlation was observed between Ca^{+2} and Mg^{+2} (r = 0.91), while Na^+ and SO_4^{2-} also showed a significant correlation (r = 0.79). These results are comparable with previous studies (Pérez-Sirvent et al. 2003; Visconti et al. 2004, 2009). In contrast to the findings of Zhang et al. (2020) and Visconti et al. (2009), the correlation between the main cations (Ca^{2+}, Mg^{2+}, and Na^+) and Cl^- demonstrated a moderate positive association (r > 0.5; P < 0.001). Additionally, in a mixture of non-saline, alkaline, saline, and saline-sodic points, higher concentrations of Ca^{2+}, Mg^{2+}, and Na^+ were found to be more strongly correlated with SO_4^{2-} than with Cl^-.

Relationship between pH value and the other variables were varied, with weak correlations associated with K^+ (r = 0.09) and HCO_3^- (r = –0.04) with P > 0.05; while weak positive correlations were observed between pH value and CO_3^{2-} (r = 0.46; P < 0.001). Furthermore, the correlations between pH value and Ca^{2+}, Mg^{2+}, EC, Cl^-, SO_4^{2-} and Na (r = 0.24–0.77) were significantly negative (P < 0.01), but slightly

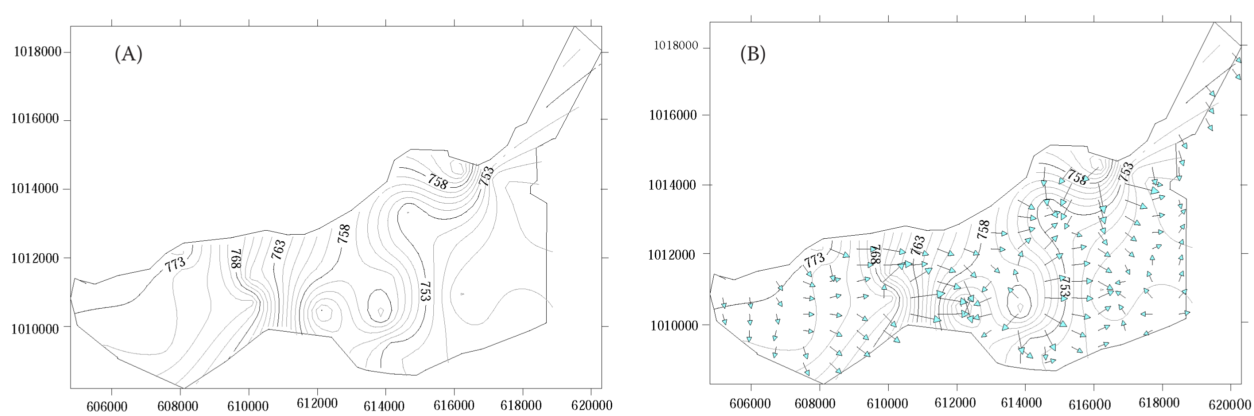

Figure 3. Groundwater table contour map (A) and groundwater flow direction (B)

https://doi.org/10.17221/37/2024-SWR

and positively with carbonate, according to the law of chemical reactions between the three ions when the pH is between 8 and 10 (Stanley & Wilkinb 2019).

Similarly, HCO_3^- values displayed weak correlations (r < 0.2; P > 0.05) with all other variables except EC (r = 0.22; P < 0.01). Moreover, CO_3^{2-} values demonstrated poor correlations with all variables except Ca^{2+}, Mg^{2+}, HCO_3^- and EC (r < 0.15; P > 0.05). The potassium cation shows the lowest correlation with the other important anions and cations (r < 0.50), similar to the results of Zhang et al. (2008), who suggest that in highly saline sites dominated by sodium and calcium.

Principal components analysis. Table 1 shows the characteristics of the first four principal components from the PCA of the standardized values of nine soil variables for both soil layers. It explains over 80% and 83% of the total variation in the top and bottom layers, respectively. The first two components explain about 60% and 63% of the total variation in the top and bottom layers, respectively. The difference between top and bottom soil is made through management, as indicated by the gap. It also revealed that the bottom layer is more homogeneous than the top layer. The average value of 61.5%, almost similar to the 59% observed by Aguilera et al. (2011) in a wetland comparable to the 64% in lowland saline soils (Visconti et al. 2009), higher than the 51% in Semi-Humid irrigated soil (Zhang et al. 2008), but lower than the 69% in an irrigated hilly region (Mora et al. 2017).

Table S2 in ESM shows the loadings /contributions of each soil variable on the four principal component axes. Given the minimal contributions of axis 3 and axis 4 to the total variance, the subsequent analysis would focus solely on the first two axes. In PC1, there is a positive correlation between calcium, magnesium, EC, and sodium ions, resulting in higher concentrations of sulphate and chloride in both the upper and lower soil layers. Conversely, PC2 reveals complex relationships where an increase in potassium leads to increased levels of carbonate and pH in the top layer, while an increase in potassium, carbonate, pH, and sulphate is associated with a decrease in bicarbonate in the bottom soil layers.

The top and bottom layers' first two PCs' ordination results are shown in Figure 5. Alkaline soil has the largest clusters of points, followed by non-saline non-sodic soil. The pH, CO_3^{2-} and HCO_3^- that defined the alkaline and non-saline non-sodic soils assigned high positive and negative values on PC1 and PC2. In contrast, significant cations and anions in saline and saline-sodic soils characterized by strong positive values on PC2 and PC1. Additional evidence of their poor association comes from the separation of potassium and bicarbonate from the other ions, which is also seen.

Main factors affecting the soil ionic composition. The RDA ordination was constrained to the three environmental and management factors: groundwater table depth below the surface (GWTD), distance from

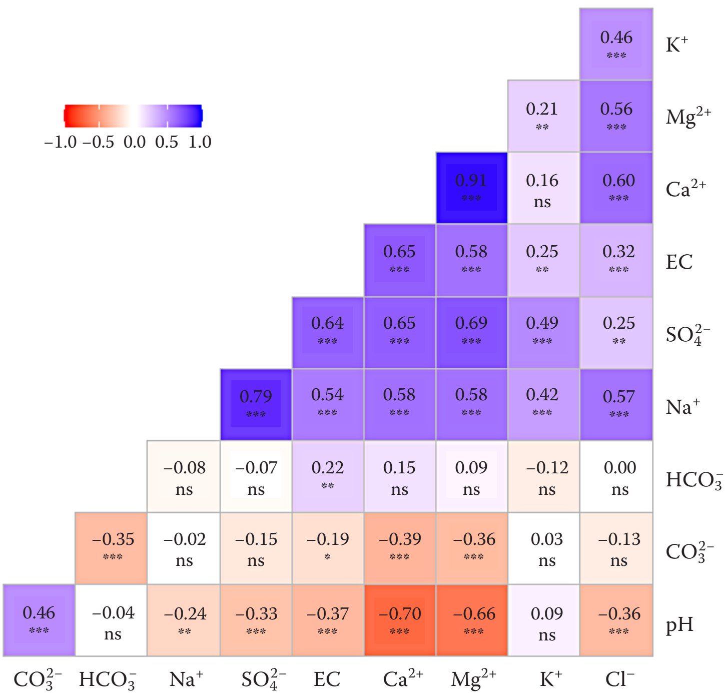

Figure 4. Pearson correlation coefficients (r) for soil chemical variables

$^{ns}P \geq 0.05$; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$

https://doi.org/10.17221/37/2024-SWR

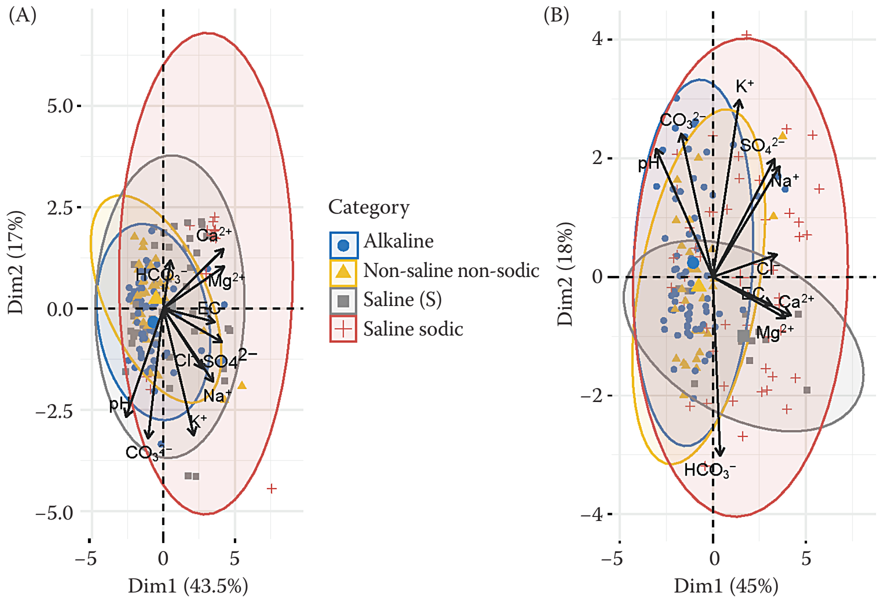

Figure 5. Biplot of individual soil samples (n = 154) and 10 variables principal component analysis (PCA) of top 0–30 cm (A) and 30–60 cm (B)

the nearest surface water body and year of irrigation application/cultivation in the Kesem area. The first two ordination axes in the RDA for median values in soil profiles account for 27% of the variance in the data (Table 2), mainly concentrated in the first axis ($\lambda 1$ = 2.5681, $\lambda 2$ = 0.16438). The first constrained axis (RDA1) explains 25.7% of the variance, while the second (RDA2) explains only 1.6%. It can be noted that the first unconstrained axis (PC1) represents 25.7% of the total variance, which is slightly less than the variance explained by the first explanatory variable; the first two unconstrained explain 41%. This means that the dataset may be structured by some additional strong environmental variable(s) different from GWTD, water body and years of cultivation.

The included environmental and management variables explain 26.77% of the variation in soil chemical composition across sites. It is higher than the value (10.1%) observed by Mora et al.(2017). Though it has low explanatory power for the soil solution composition (26.77% of the variance explained), our full model is statistically significant ($P < 0.001$), and the test of canonical axes show that RDA1 and RDA2 are statistically significant at $P < 0.001$ and $P < 0.05$, respectively (Table 3). The groundwater table variable included in this model mainly determines the soil's chemical composition ($P < 0.001$). The other two environmental and management factors (year of cultivation and distance of water body) were less relevant or redundant ($P > 0.05$).

Salt ions tend to accumulate more in areas where shallow groundwater is present (Table 4). The contribution of groundwater to RDA1 is significant ($P < 0.001$), with a negative contribution of (98.9%), the largest of the three factors. The irrigation practices are the second most likely contributor to RDA1 (51.7% at $P < 0.05$). Distance to the nearest water body contributes the least of all. Similarly, Qian et al. (2017) noted that groundwater salinity and plant cover are the key variables affecting soil salinity in the sparse grassland, with distance to the nearest irrigation canal being the least significant factor. The salinity of cropland was, however, most significantly influenced by the distance to the closest irrigation canal. Soil salinity increased with distance from the canal. This is attributed to the effective leaching

Table 2. Eigenvalues, and their contribution to the correlations in redundancy analysis (RDA)

Importance of components	RDA1	RDA2	RDA3	PC1	PC2	PC3
Eigenvalue	2.57	0.16	0.03	2.53	1.62	0.98
Proportion explained	0.257	0.016	0.003	0.253	0.162	0.098
Cumulative proportion	0.257	0.273	0.276	0.529	0.691	0.789

https://doi.org/10.17221/37/2024-SWR

Table 3. Statistical test analysis of redundancy analysis (RDA)

	df	Variance	*F*	*P* (> *F*)
Permutation test for RDA under reduced model				
Model	3	2.7596	19.057	0.001***
Residual	150	7.2404		
Test of all canonical axes				
RDA1	1	2.5681	53.2033	0.001***
RDA2	1	0.1644	3.4054	0.026*
RDA3	1	0.0272	0.5632	0.725
Residual	150	7.2474		
Anova. cca (rda.signif, step = 1 000, by = „term“)				
Groundwater table depth	1	108.006	55.7005	0.001***
Distance to the water body	1	4.232	2.1826	0.101
Irrigation year	1	2.041	1.0528	0.328
Residual	150	290.857		

df – degree of freedom; *P* – probability; *,***significant at 5%, 0.1% level

Table 4. Biplot scores for constraining variables

Factor	RDA1	RDA2	RDA3
GWTD	(0.99)	(0.06)	0.13
Distance of water body	(0.02)	0.94	(0.34)
Irrigation year	(0.52)	(0.49)	(0.70)

RDA – redundancy analysis; GWTD – groundwater table depth below the surface; () – negative value of the number

of salts from the topsoil due to the use of fresh river water for irrigation.

Irrigation water in the study area tends to reduce salt ions through leaching, which in turn is influenced by other soil physical properties. This result contradicts the common belief that repeated irrigation tends to induce soil salinization, either by adding salt to the soil or by transporting weathered soil salt minerals from the bottom to the surface. This is attributed to the high-quality irrigation water in terms of salinity as it originates from the highland areas (Kidia et al. 2019), which instead plays a leaching role in the study area.

CONCLUSION

The descriptive analysis of the composition of soil-soluble cations and anions clearly demonstrated the relative content of the ions and their change in concentration with soil depth. Pearson's correlation analysis revealed the ionic compositions of soil samples have variable correlation coefficients, with the strongest correlations being between Ca^{+2} and Mg^{+2}, and sodium and sulphate.

The study showed that soils of the study area were laterally varied, where large areas are affected by salinity in both top and bottom layers. The PCA made it possible to separate the four primary soil domains of non-saline non-sodic, alkaline, saline and saline-sodic.

The use of multivariate analysis in the current study clarified the role of the studied explanatory factors in the variation of soil salinity, notwithstanding the moderate explanatory power for the soil ion composition. This suggests that there are other environmental and management factors that were not considered. Future research should include these factors to improve our understanding of soil salinity. By using MVA, we can better understand the relationships between groundwater levels and management practices on soil salinity. This highlights the management strategies that should be used in light of the major environmental factor affecting the salinity characteristics of the region.

REFERENCES

Aguilera H., Moreno L., Jiménez-Hernández M.E., Castaño S., la Losa A.D. (2011): Management implications inferred from the multivariate analysis of vadose zone chemical variables in Las Tablas de Daimiel NationalPark (Spain). Geoderma, 162: 365–377.

Basavaraja P.K., Sharma S.D., Badrinath M.S., Sridhar A.S., Hareesh G.R. (2007): *Prosopis juliflora* – An efficient tree species for reclamation of salt affected soils. Karnataka Journal of Agricultural Sciences, 20: 727–731.

https://doi.org/10.17221/37/2024-SWR

Cui G.Q., Lu Y.D., Zheng C., Liu Z.H., Sai J.M. (2019): Relationship between soil salinization and groundwater hydration in Yaoba Oasis, Northwest China. Water, 11: 1–19.

FAO (1984): Physical and Chemical Methods of Soil and Plant Analysis. FAO Soils Bulletin No. 10. FAO, Rome.

Gupta P.K. (2004): Methods in Environmental Analysis: Water, Soil and Air. Rajasthan, Agrobios Publishing.

Hesse P.R. (1971): A Textbook of Soil Chemical Analysis. London, John Murry, Ltd.

Johansson M., Stenberg B. (2000): Multivariate techniques for presentation, interpretation and evaluation of soil quality data. DIAS Report. Plant Production (Denmark): 63–72.

Kidia K.G., Zehetner F., Loiskandl W., Klik A. (2019): Effects of soil texture and groundwater level on leaching of salt from saline fields in Kesem irrigation scheme, Ethiopia. Soil and Water Research, 14: 221–228.

Landon J.R. (1991): Booker Tropical Soil Manual. A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Essex, New York, Longman Scientific and Technical.

MacDonald & Partners (1987): Kesem Irrigation Project Feasibility Study, Final Report. Vol. 1: Main Report. Cambridge.

Makowski D., Ben-Shachar M.S., Patil I., Lüdecke D. (2020): Methods and algorithms for correlation analysis in R. Journal of Open Source Software, 51: 2306.

Momtaz H.R., Jafarzadeh A.A., Torabi H., Oustan S.H., Samadi A., Davatgar N., Gilkes R.J. (2009): An assessment of the variation in soil properties within and between landform in the Amol Region, Iran. Geoderma, 149: 10–18.

Mora J.L., Herrerob J., Weindorf D.C. (2017): Multivariate analysis of soil salination-desalination in a semi-arid irrigated district of Spain. Geoderma, 291: 1–10.

Pérez-Sirvent C., Martınez-Sánchez M.J., Vidal J., Sánchez A. (2003): The role of low-quality irrigation water in the desertification of semi-arid zones in Murcia, SE Spain. Geoderma, 113: 109–125.

R Core Team (2022): R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available on https://www.R-project.org/

Qian T., Tsunekawa A., Masunaga T., Wang T. (2017): Analysis of the spatial variation of soil salinity and its causal factors in China's minqin oasis. Mathematical Problems in Engineering, 2017: 745264.

Richards L.A. (1954): Improvement and management of soils in arid and semiarid regions in relation to salinity and alkali. In: Richards L.A. (ed.): Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60. Washington D.C., United States Salinity Laboratory Staff: 34–54.

Rhoades J.D. (1992): Instrumental field methods of salinity appraisal. In: Topp G.C., Reynolds W.D., Green R.E. (eds.): Advances in Measurements of Soil Physical Properties: Bringing Theory into Practice. Madison, SSSA Special Publication 30/ASA/CSSA/SSSA: 231–248.

Rhoades J.D., Chnduvi F., Lesch S.M. (1999): Soil Salinity Assessment: Methods and Interpretation of Electrical Measurements. FAO Irrigation and Drainage Paper No. 57. Rome, FAO.

Ruff D., Loiskandl W., Spendlingwimmer R., Schönerklee M., Awulachew S.B., Boelee E., Wallner K. (2007): Environmental impact analysis of two large scale irrigation schemes in Ethiopia. IIPE Symposium Paper. Addis Ababa, International Water Management Institute (IWMI): 370–388.

Stanley D.M., Wilkin R.T. (2019): Solution equilibria of uranyl minerals: Role of the common groundwater ions calcium and carbonate. Journal of Hazardous Materials, 377: 315–320.

Taddese G. (2001): Land degradation: A challenge to Ethiopia. Environmental Management, 27: 815–824.

Visconti F., de Paz J.M., Zapata R., Sánchez J. (2004): Development of an equation to relate electrical conductivity to soil and water salinity in a Mediterranean agricultural environment. Australian Journal of Soil Research, 42: 381–388.

Visconti F., José M.D.P., José L.R. (2009): Principal component analysis of chemical properties of soil saturation extracts from an irrigated Mediterranean area: Implications for calcite equilibrium in soil solutions. Geoderma, 151: 407–416.

Webster R., Oliver M.A. (1990): Statistical Methods in Soil and Land Resource Survey. New York, Oxford University Press.

Yarima B.P.K. (1993): Manual for Good Laboratory Practice. Addis Abeba, Land Use Planning and Regulatory Department, Ministry of Natural Resources Development and Environment Protection.

Zaman M., Shahid S.A., Heng L. (2018): Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques. Cham, Springer Open.

Zhang C., Fay D., McGrath D., Grennan E., Carton O.T. (2008): Statistical analyses of geochemical variables in soils of Ireland. Geoderma, 146: 378–390.

Zhang J., Du D., Ji D., Bai Y., Jiang W. (2020): Multivariate analysis of soil salinity in a semi-humid irrigated district of China: Concern about a recent water project. Water, 12: 10.3390/w12082104.

Received: April 10, 2024
Accepted: September 4, 2024
Published online: October 10, 2024