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Spatial Variability and Analysis of Key Soil Properties in the Kesem Irrigation Scheme, Awash River Basin, Ethiopia

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

[1]Department of Water Resources Engineering, Adama Science and Technology University, Adama, Ethiopia
[2]Water Resources Management Group, Wageningen University and Research, Wageningen, The Netherlands
[3]Agricultural water Management Research. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia
**Correspondence: mengistubosie@gmail.com*

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Abstract: The Kesem Irrigation Scheme, located in the middle Awash River Basin of Ethiopia faces significant challenges due to widespread soil salinity and sodicity, hindering its agricultural productivity. This study aims to assess the spatial distribution and extent of soil salinity and evaluate the spatial variability of key soil properties in southern block of the scheme, encompassing 5000 hectares. A total of 154 composite soil samples were collected from both active sugarcane fields and abandoned areas at 0-30 cm and 30-60 cm depths. Soil properties analyzed included particle size distribution, pH, electrical conductivity (ECe), exchangeable sodium percentage (ESP), and exchangeable cations. Geostatistical analysis, including semivariogram modeling and ordinary kriging, was employed to assess the spatial variability of soil properties. Descriptive statistics, normality tests, and paired t-tests were performed. Soil textural classes were determined, and soil salt classes were classified based on ECe, ESP, and pH Soil texture analysis revealed a predominance of silt and clay fractions, while soil assessment identified four salt classes: non-saline, saline, saline-sodic, and alkaline based on FAO techniques. Results showed that pH had the lowest coefficient of variation (CV), while the ECe had the highest CV. Variability was generally greater in the bottom layer, except for cation exchange capacity (CEC) and ESP. Prosopis Julifera-infested areas had substantially lower ECe and ESP, with increased pH. Geostatistical analysis showed moderate to strong spatial dependence for most soil properties within a range of 861-6186 meters. The dominance of silt-dominated soils increases the risk of sodium retention, exacerbating salinity and sodicity issues. Elevated salinity and sodicity levels were observed in certain areas, attributed to factors such as groundwater table rise and inadequate drainage. This study provides valuable information for developing site-specific soil management strategies to enhance agricultural productivity and ensure sustainable agricultural land use. Further research is essential to determine the specific roles of various soil salinity factors in influencing soil properties within irrigated agricultural systems.

Keywords: Salinity, Sodicity, Prosopis Julifera, Geostatistics, Kriging, Soil Management

INTRODUCTION

Soil is a heterogeneous, diverse, and dynamic system, and its properties change in the time and space continuum (Cichota et al., 2006). Variability may occur at a large scale (region) or a small scale, even in the same type of soil or fine scale (Feng et al., 2008; Coutts et al., 2021). The variability of natural soils is well known in its formation factors interacting within the landscape. Characterization and soil spatio-temporal variability analysis is essential to achieve a better understanding of complex relations between soil properties, environmental factors, and land use systems. Among, environmental factors, rewetting has a high potential to increase the heterogeneity of surface soils because of groundwater dynamics, sedimentation depositions from the surrounding landscapes, and occasional flooding by nearby freshwater resources (Ahmad et al., 2020a; Ahmad et al., 2020b).

Soil physico-chemical properties exhibit significant spatial variability across landscapes, influenced by both intrinsic factors (e.g., parent material, topography) and extrinsic factors such as crop rotation, soil management practices, and fertility levels (Cambardella & Karlen, 1999). Soil properties are further shaped by landforms, geomorphic processes, and soil-forming factors (Buol et al., 1997). Cemek et al. (2007) and Some'e et al. (2011) also demonstrated the strong influence of extrinsic factors like groundwater levels, drainage, irrigation, and microtopography on soil salinity and alkalinity. Kesem irrigation project is the most recent developed public sugar development project in the Awash River basin of Ethiopia. Large fields of the project have been suspected to be salt affected soils with visible features of white and brown salt crusts on their surface. Most of the abandoned area has been covered with exotic plant called Prosopis Juliflora. In the Kesem Irrigation project, widespread salinity and sodicity have severely hampered crop production (Zeleke et al., 2014; UNDP/FAO, 1987). This situation poses a significant challenge to the project's economic viability and its ability to contribute to national sugar production and energy generation goals. To understand the effects of land use and management on soil characteristics, it is essential to monitor and measure fluctuations in soil attributes.

Soil survey provides a precise and scientific inventory of different soil types, their nature, and the extent of their distribution so that one may predict their characteristics and potentialities (Denton et al., 2017). Similarly, Tesfahunegn et al. (2011), Some'e et al. (2011) and Khan et al. (2021) suggested scientific understanding of the spatial variability and distribution of soil properties is crucial for the design of sustainable soil, crop and environmental management strategies. Users therefore, need precise statistical data on the distribution and variability of soil qualities in order to use and manage land.

Geo-statistics has been widely used in modeling spatial variability in soil properties and mapping spatial distribution. Geo-statistics, which can be defined as tools to study and predict the spatial structure of geo-referenced variables, provides a set of tools to illustrate spatial variability in a variety of natural phenomena (Webster & Oliver, 2007) and the spatial properties of soil attributes. On the other hand, the conventional soil sampling method and standard statistical analysis, such as analysis of variance, assume soil samples are spatially independent (Cambardella et al., 1994). However, soil properties are not always spatially independent. Therefore, the objective of this study was to assess the spatial distribution and severity of soil salinity, and evaluate the spatial variability of other key soil properties within the Kesem irrigation project level within the Awash River Basin, Ethiopia.

MATERIALS & METHODS

Study area description

The Kesem Irrigation scheme in the Awash River basin, established to cultivate over 20,000 hectares of sugarcane to supply a sugar factory and ethanol plant, has fallen short of its ambitious goals. After more than 15 years of operation, less than 3,000 hectares of sugarcane are currently being cultivated. The primary constraint to achieving full production capacity is the widespread presence of salinity and sodicity in the majority of the command area (Zeleke et al., 2014; UNDP/FAO, 1987).

Kesem southern irrigation project, part of Kesem irrigation scheme is located between 9°7' and 9°12' north latitude, and 39°57' to 40°5' east longitude, in the main rift valley in the Awash River basin of Ethiopia (Figure 1). It covers an area of 50 km2 (or 5000 hectares). Kesem River forms its northern border, while the Deho swamp forms its southern and eastern boundaries.

The main part of the state farm, at Western part, is an old scheme that has been extended over the decades. It was started in 1905 by a Frenchman whose name, was Saboret. Since 2007 it has been part of Kesem irrigation expansion project. It employs a conventional block-ended furrow irrigation system with individual furrows ranging from 100 to 200 meters in length. Some areas of the project were initially affected by problems of salinity and/or sodicity (UNDP/FAO, 1987). The abandoned areas of the scheme are largely covered by the invasive plant Prosopis juliflora, a rapidly growing fuel wood species known for its ability to thrive in diverse soil conditions, including degraded lands, saline soils, and waterlogged areas (Basavaraja et al., 2007).

Soil sampling and laboratory analysis

The southern block of the Kesem irrigation scheme features a mix of active sugarcane fields and abandoned areas, primarily due to salinity issues. Sampling was conducted in these fields during the dry season of 2022. The fields are generally rectangular in shape and vary in size from 1.5 to 30 hectares. Composite soil samples were collected from each field unit at two depths (0-30 cm and 30-60 cm), totaling 154 samples per soil layer. Five auger samples were taken in a cross pattern (X) to create each composite sample. Sampling sites were evenly distributed across the study area, with limited exceptions due to inaccessibility. A potential limitation of this study is the exclusion of inaccessible areas, such as fields inundated by groundwater and those waterlogged due to the expanding Filweha stream in the eastern outskirts. While these areas were not sampled, their exclusion is not expected to significantly alter the overall findings of this study, as they represent a relatively small portion of the overall study area.

The soil samples were air-dried, grinded using a standard soil sample grinding machine and allowed to pass through a 2 mm sieve. Soil particle size analysis was undertaken for both layers using hydrometer method (Beretta et al., 2014).

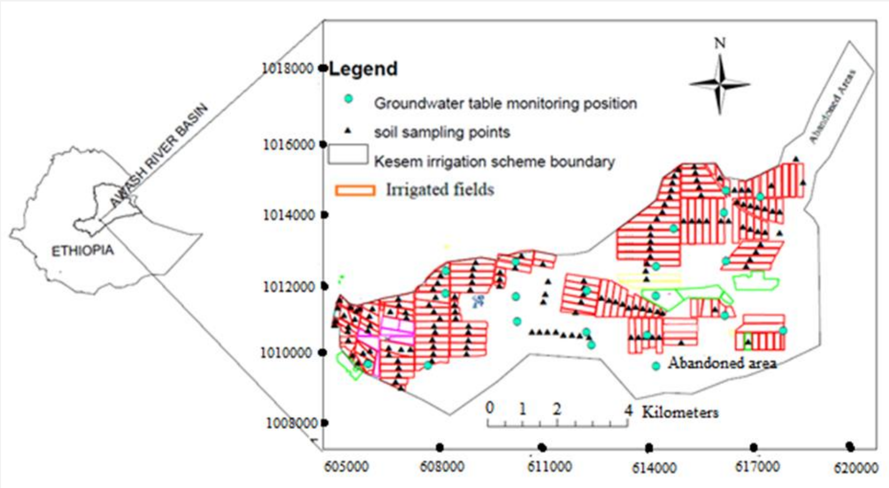

Figure 1. Map of study area.

A soil-water suspension with a ratio of 1:5 was prepared following the methods described in Gupta (2004). Soil pH was measured using a digital pH-meter and electrical conductivity (EC) by digital conductivity meter according to the method outlined by Richards (1954) and Rhoades et al. (1999), respectively. The value of salt concentration of each sample (EC 1:5 reading) was converted to saturation paste extract (ECe) by multiplying with conversion factor as suggested by Yarima (1993).

Basic exchangeable cations (Ca, Mg, K and Na) were extracted by saturating the soil sample with neutral ammonium acetate (1N NH4OAc) solution. Exchangeable Ca and Mg were measured using ETDA titration method and exchangeable K and Na were measured by flame photometer (FAO, 1984). Exchangeable sodium percentage (ESP) was calculated from the exchangeable sodium as percent retained by the CEC as in equation 1:

$$ESP = \frac{Na}{CEC} * 100 \quad (1)$$

where, ESP in percent (%), Na and CEC in meq/100g.

Spatial Exploratory Data Analysis (SEDA) was performed using ggplot package within the Rstudio environment (Wickham, 2016) to investigate the spatial distribution of soil particle size and exchangeable cations.

Geospatial analysis of salt affected soils

Geostatistics was used to examine the spatial variability of salt-affected soils. To interpolate the values of un sampled places and create maps, the ordinary Kriging interpolation method was utilized (Singh et al., 2011). The kriging interpolation method has high application due to minimizing of error variance with unbiased estimation (Pohlmann, 1993; Khan et al, 2021). The scatter point set was used to construct a semivariogram that was then used to interpolate, and the input point data set was used to quantify the spatial variations. The average squared difference in Z-value between sample points separated by h is theoretically the value of the semivariogram for a separation distance of gamma h (also known as the lag distance) (Mohammadi, 2002). Equation 2 illustrated the semivariogram as (Mousavifard et al, 2013):

$$\gamma(h) = \frac{1}{2}\sum_{n=1}^{n}[Z(Xi) - Z(Xi+h)]^2 \quad (2)$$

where: - n is the number of pairs of sample points separated by the distance h and Z (Xi)'s the value of the characteristic under study at i^{th} location (i = 1, 2, 3… n).

Statistical analysis

Using Minitab v.17, descriptive statistics mean, median, maximum, minimum, and coefficients of variation (CV) were computed for each soil parameter. The data were checked for normality (Shapiro. test) before being used to create variograms. With the aid of a geo-statistical software called QGIS 3.28.3, geo-statistical analysis was carried out, including the creation of sample variograms and kriging.

According to the United States department of agriculture (USDA) soil texture classification system, soil textural classes were attached using the RStudio AppendTextureclass function (Omuto, 2022; Moeys, 2018). The soil texture proportions of clay, silt, and sand in percentages were displayed in columns of a spatial pixel data frame. The depth of the textural variability was tested for homogeneity of variances with Bartlett-test.

A function of saltClass in RStudio was used to determine the major classes of salt-affected soils' electrical conductivity in dS/m of saturated soil paste extract (ECe)or its equivalent, soil reaction (pH), and exchangeable sodium percent (ESP) according to the FAO classification (Zaman et al., 2018). SaltClass model returns integer classes of salt problems in the soil. The classes are 1, 2, 3, 4, and 5 corresponding to the None, Saline, Saline-sodic, Sodic, and Alkaline categories.

Paired samples t-tests were conducted to compare soil pH, ECe, and ESP values between upper (0-30cm) and lower (30-60cm) for both currently irrigated/cultivated fields and abandoned fields. The analysis included the calculation of mean difference, confidence intervals, standard deviation of the difference, standard error of the mean (SEM), and p-values to assess the statistical significance of the observed differences.

Cross-validation of the predicted model

In cross-validation, the values estimated by ordinary kriging were applied and contrasted with the values seen 154 sampling locations in the study area. The performance of the kriging interpolation was then evaluated using various indices, including mean prediction error (ME) (equation 3) and root mean square standardized prediction error (RMSSE) (equation 4) between observed and predicted soil variables in the cross-validation (Webster and Oliver, 2007). The general methodology applied in this study is presented in Figure 2.

$$ME = \sum_{i=1}^{n} \frac{z^*(x) - z(x)}{n} \quad (3)$$

$$RMSSE = \sqrt{\frac{\sum_{i=1}^{n} [\left(\frac{z^*(x) - z(x)}{n}\right)^2 / \sigma^*(x)]^2}{n}} \quad (4)$$

where, n is number of samples, z(x) is a measured value, z*(x) is a predicted value, and σ*(x) is the variance in the predicted value.

RESULTS & DISCUSSION

Soil particle spatial distribution and their textural classes

The analysis showed that the size distributions of the soil particles vary considerably. Clay particle distribution had the largest contribution in the range of 9.2% to 82.8%, followed by silt (10 to 75.6%). Sand had the smallest share with 1 to 47% (Figure 3). Extreme spatial differences in the size distribution of soil particles indicate that this phenomenon has been common throughout the area for some time (UNDP/FAO, 1987). Corresponding soil texture classes of the study area are listed in Table 1. In general, six texture classes are determined. Among these, the most important texture classes are clay (35.3%), Silt clay (22.8%), Silt loam (16.3%), and Silty clay loam (15.5%), occupying about 90% of the area share. Soil textures vary significantly, reflecting the very complex recent geomorphological and hydrological history of the area. Alluvial fans continue to be developed, as meandering watercourses repeatedly alter their courses (UNDP/FAO, 1987).

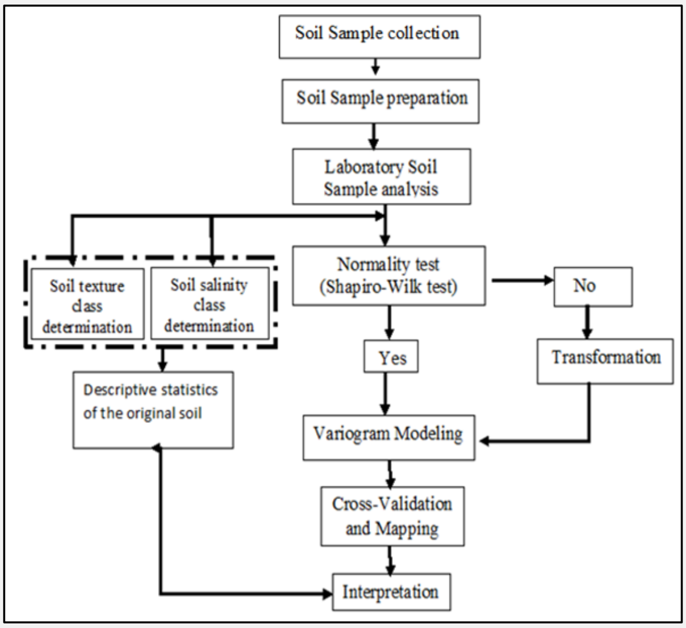

Figure 2. Methodological flow chart of soil analysis.

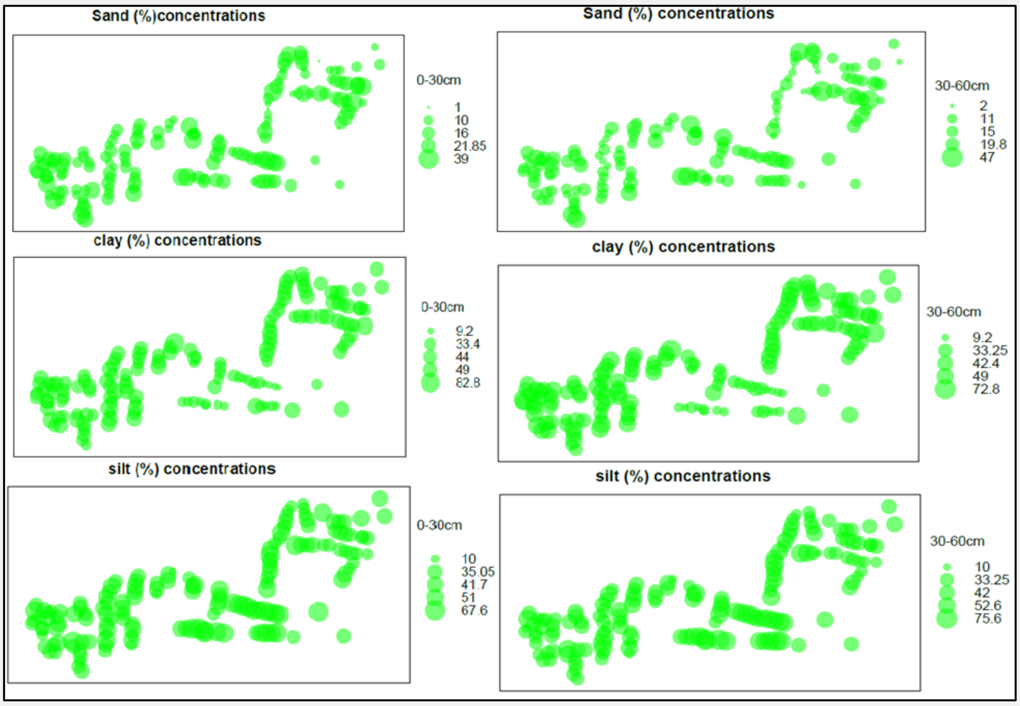

Figure 3. Bubble concentration of soil particle distribution.

Table 1. Soil textural class and their percent share in the study area

S.N	textural class	no of fields	ha	% area share
1	Clay	63	831.74	35.3
2	Silty clay	30	538.47	22.8
3	Silt Loam	23	383.98	16.3
4	Silty Clay Loam	22	366.29	15.5
5	Clay Loam	13	167.98	7.1
6	Loam	3	70.46	3.0

Since all the p-values of the Bartlett test (Table 2) exceeded 0.05, the result suggests the soil is homogenous in texture.

Table 2 Bartlett Homogeneity Test (alpha = 0.05) (n= 307)

Data	Test statistics (Bartlett's K-squared)	Parameters (df)	P-Value
Sand by depth	1.1402	1	0.2856
Clay by depth	0.50376	1	0.4779
Silt by depth	0.75571	1	0.3847

The soils in the study area were predominantly silt-clay in composition, consistent with previous findings (UNDP/FAO, 1987; Zeleke et al., 2014). Specifically, silt/clay ratios for the 0-30 cm and 30-60 cm depths ranged from 0.23 to 6.83 and 0.19 to 6.45, respectively. These ratios consistently exceeded 0.15, indicating relatively young and weatherable soils, as suggested by van Wambeke (1962). However, this contrasts with the findings of Sharu et al. (2013) in Sokoto State, Nigeria.

The order of concentration of exchangeable cations followed nearly similar trend in the top and bottom (Figure 4). The average concentration of the exchangeable cation from highest to lowest follows $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$. Large areas of the study area are alkaline soil with pH > 8. Higher exchangeable Na^{+} (> 1meq/100g) created a potentially alkaline soil environment (Richards, 1954; Landon, 1984). The abundance of silt soil in the study area puts the soil solum at greater risk for excessive sodium retention and leaching. Due to their small size, clay particles of a given size have a much larger surface area than those of the same volume of coarser texture soil.

All fields have high to very high cation exchangeable capacity (CEC) (11.22-103.7 meq/100g) (Landon, 1984). The cation exchangeable capacity of clay and Clay loam soils was in the range of 31 to 90 meq/100g. In general, higher-CEC soils (greater than 10 meg/100g), on the other hand, experience little cation leaching, thus making high reserves of exchangeable cations.

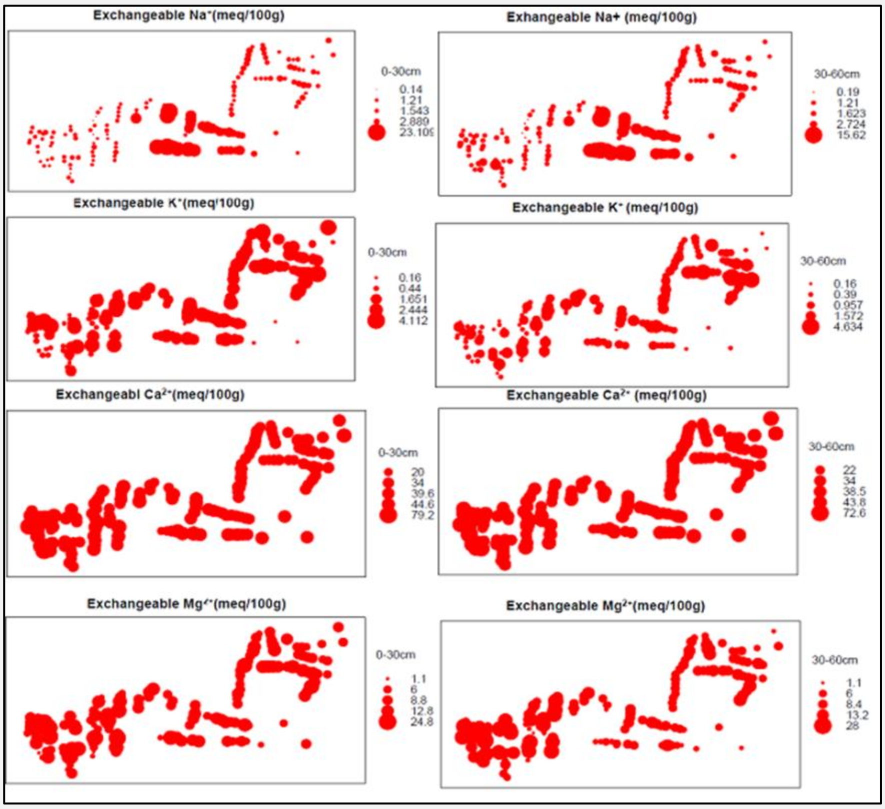

Figure 4. Measured concentration of soil exchangeable cations.

Descriptive Statistics of Major Soil Properties in the Study Area

Table 3 showed summary data for soil pH, ECe, ESP, CEC, and soil particle content of sand, clay, and silt. The average pH of the soil in both the 0-30 cm and 30-60 cm layers was measured to be 8.2, with values ranging from 7 to 10. 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 (1984). The results of the investigation showed that the ECe values for all of the fields under consideration ranged from a minimum of 0.7 to a maximum of 112.38 ds/m. Most of the fields have lower salinity levels at the bottom (30–60 cm) than in the top (0–30 cm) layers, suggesting that water movement may be the source of salinity and that it originates in the lower layer of the soil.

Measured soil chemical properties showed that ECe and ESP levels were relatively higher in the middle and northeast of the study area close to shallow groundwater and Filweha River banks (marshy areas). Patches of soil affected by varying degrees of salinity were also found, with strongly saline-sodic soils, particularly in the vicinity of the abandoned fields. This showed the source of soil salinity could be rise of saline ground water.

The Shapiro-Wilk test primarily indicated normal distributions for most soil properties (Table 4), suggesting they generally followed a normal distribution. However, exceptions were observed for ECe, ESP, and Sand content in both soil layers. Moreover, the analysis demonstrated that the majority of soil properties showed comparable mean and median values across the study area. While mean values were generally slightly higher than median values (Table 4), this suggests a generally symmetrical distribution of data around the central tendency. Similar research findings were also reported by Cambardella et al. (1994) and Khan et al. (2021).

All of the measured variables had very large coefficients of variation (CV), with ranges of 5.34-127.01% and 5.76-172.96% at depths of 0–30 cm and 30–60 cm, respectively. The lowest coefficient of variation (CV ≤ 15%) was observed in pH with a value of 5.34%, which could be a result of the uniform conditions in the area such as little changes in slope and its direction leading to a uniformity of soil in the area (Wani et al., 2017; Denton et al., 2017; Khan et al, 2021), while electrical conductivity (127.01 and 172.96 %) had the highest variation at both soil depths. Exchangeable sodium percentage (ESP) and sand content also showed high variability (CV ≥ 35%). While moderate variability (CV = 15–34%) was found for cation exchangeable capacity (CEC), silt content, and clay content according to the guidelines provided by Warrick (1998) for the variability of soil properties. These variations in chemical properties are mostly related to the different soil management practices carried out in the study area, the parent material on which the soil is formed, the role of the depth of groundwater, environmental factor, and irrigation water quality (Anderson et al., 2005; Wani et al., 2017). Specifically, the presence of *Prosopis juliflora* (a fast-growing invasive tree) and the rise of saline groundwater are recognized as major factors contributing to the observed variations in soil chemical properties (Jiru et al., 2024).

Table 2. Summary statistics of the original soil variables (sample population, n = 154)

Variable	unit	Mean	CV (%)	Median	Minimum	Maximum
0-30cm						
pH	-	8.25	5.34	8.32	7.18	10.05
ECe	(dsm^{-1})	6.20	127.01	2.36	0.70	43.20
CEC	(meq/100g)	55.33	23.07	53.99	31.32	90.58
ESP	(%)	5.67	118.44	3.16	0.21	44.24
Sand	(%)	16.51	48.71	16	1.00	39.00
clay	(%)	40.91	30.20	44	9.20	82.80
silt	(%)	42.58	28.72	41.7	10.00	67.60
30-60cm						
pH	-	8.22	5.76	8.28	6.99	10.07
ECe	(dsm^{-1})	7.90	172.92	2.2	0.94	112.38
CEC	(meq/100g)	52.30	21.87	51.78	11.22	103.70
ESP	(%)	5.55	107.17	3.35	0.27	32.40
sand	(%)	16.41	53.29	15	2.00	47.00
clay	(%)	40.32	32.35	42.4	9.20	72.80
silt	(%)	43.27	30.23	42	10.00	75.60

CV= coefficient of variation, ECe = electrical conductivity of saturated paste, ESP= Exchangeable sodium percentage, and CEC = cation exchangeable capacity.

Table 4 showed the results of paired t-test analysis for pH, ECe, and ESP on irrigated and abandoned areas. A slight decline in ECe and ESP with depth can be seen in irrigated areas. The paired t-test did not reveal any statistically significant differences in the irrigated fields. In contrast, in the abandoned fields, there was a significant difference in pH and ECe between the upper soil layers and the lower soil layers

Generally, salinity is relatively low in irrigated fields compared to abandoned fields (Table 4). In irrigated areas, ECe and ESP were lower and relatively uniform, with increasing soil depth as the soil is leached by good quality water (Gelaye et al., 2019), presumably due to an increase in saline groundwater in the soil profile or restricted drainage. On the other hand, the topsoil in non-cultivated fields has a lower ECe compared to the bottom soil with no irrigation, which indicates a source of salinity was from the bottom layer of the soil and brought up by water movement (capillary). Similarly, Georgis et al. (2006) indicated, the surface soils (0-20cm) were severely saline and slightly saline, but subsoil layers of 20-40 and 40-60 cm depths, in the abandoned land of Melka Sedi-Amibara Plain of Middle Awash were severely saline and very severely saline respectively.

Table 3. Paired sample t-test of soil salinity in upper and lower layers

Variables		M^a	MD^b	SD^c	Std. error mean	95% confidence interval of difference		t	DF^d	P-value
						0-30 cm	30-60 cm			
Irrigated fields										
pH	0-30cm	8.269	-0.0007	0.372	0.3782	-0.068	0.067	-0.02	121	0.985
	30-60cm	8.270								
ECe	0-30cm	5.238	0.155	7.504	0.679	-1.190	1.50	0.23	121	0.820
(dsm^{-1})	30-60cm	5.083								
ESP(%)	0-30cm	4.073	0.020	2.60	0.235	0.445	0.049	0.09	121	0.931
	30-60cm	4.052								
abandoned										
pH	0-30cm	8.187	0.1487	0.326	0.0577	0.0311	0.266	2.58	31	0.015
	30-60cm	8.038								
ECe	0-30cm	9.88	-8.68	22.10	3.91	-16.65	-0.71	-2.22	31	0.034
(dsm^{-1})	30-60cm	18.56								
ESP(%)	0-30cm	11.73	0.675	3.562	0.630	-0.609	1.959	1.07	31	0.292
	30-60cm	11.06								

M^a = mean; MD^b = mean difference; SD^c = standard deviation; DF^d = degree of freedom.

Types and Distribution of Salt Affected Soils

The results of the soil salt class types of the study area from the soilassessment model (Omuto, 2022) are shown in Table 5. Four salinity classes have been identified; non-saline, saline, saline-sodic, and alkaline categories. Their distribution was similar in both the upper and lower layers, being of the order of 42.5%, 29%, 18.5%, and 10% for the alkaline, saline, non-saline, and saline-sodic classes, respectively. Taken together, non-saline and alkaline soils were the dominant classes (more than 60%). The main difference between non-saline and alkaline soil is that the pH of non-saline soil varied slightly between 7.9 and 8.1 while the pH of alkaline soil ranged from 8.4 to 8.6. While both ECe and ESP were less than 4 dsm^{-1} and 15%, respectively, for both non-saline and alkaline soils. The widespread occurrence of alkaline soils in semiarid and arid regions, as documented by López-Bucio et al. (2000), is expected to result in a significant proportion of area share. Alkaline soils typically exhibited lower soluble calcium content compared to saline soils. In general, large samples of clay soils with a pH of 8.4 to 8.6 were classified as alkaline soils. If not well managed, alkaline soils can worsen, often transitioning into more severe salt-affected conditions, primarily saline-sodic. This deterioration could be aggravated by poor drainage, excessive irrigation, and the use of low-quality irrigation water.

Saline soils are soils with a saturation extract conductivity greater than 4dSm^{-1} and an exchangeable sodium fraction of less than 15% (Zaman et al., 2018). The pH is usually below 8.5. Most saline soil samples (55-62%) were from silty loam/loam and/or silty clay-loam/clay-loam soil layers. Although categorized under saline soil, exchangeable cations were also present to an appreciable extent to cause sodicity in the layer. These soils frequently exhibit permeability comparable to or even exceeding that of similar normal soils. This salinity typically arises from a combination of rising groundwater levels and inadequate drainage. These soils are commonly found in tropical regions characterized by arid conditions and high rates of evaporation, which further contributes to salt accumulation (CHHABRA, 2004).

Saline-sodic soil is defined as soil with a saturation extract conductivity greater than $4dSm^{-1}$ and an exchangeable sodium percentage greater than 15 (Zaman et al., 2018). Soil pH in saline-sodic soils is variable and typically exceeds 8.5, influenced by the relative proportions of exchangeable sodium and soluble salts. A significant majority (75-80%) of these soils were found in silty loam/loam and silty clay-loam/clay-loam textural classes. Conversely, this soil class represented the smallest proportion (10%) among all soil types.

Table 4. Soil salt classes and their physico-chemical properties

S.N.	Soil salinity and chemical property				Soil texture and No. of samples				
	Salt class	pH	Ece (ds/m)	ESP (%)	C	SiC	SiL/L	SiCL /CL	Total No. of Samples
				0-30cm					
1	None saline-None sodic	7.9-8.13	0.7-3.98	1.1-9.22	15	5	5	4	29
2	Saline	7.69-8.48	4.02-43.20	0.21-14.01	10	7	9	19	45
3	Saline-sodic	7.68-8.62	8.85-23.11	15.0-44.27	1	3	10	2	16
4	Alkaline	8.38-8.63	1.0-3.99	0.34-14.09	33	4	5	22	64
				30-60cm					
1	None saline-None sodic	7.97-8.06	1.05-3.23	1.35-12.07	10	5	5	8	28
2	Saline	7.75-8.44	4.04-34.11	0.27-13.57	12	8	11	14	45
3	Saline-sodic	7.33-7.84	8.91-112.36	15.32-32.4	2	1	11	1	15
4	Alkaline	8.39-8.65	0.94-3.74	0.27-12.36	38	12	3	13	66

Note: C =Clay, SiC =Silty clay, SiL/L =Silty Loam/Loam, and SiCL/CL= Silty clay Loam/ Clay Loam.

Temporal Changes in Soil Chemistry of Salt-Affected Fields (2014-2021) is shown in Table 6. A significant decrease in both Electrical Conductivity (ECe) and Exchangeable Sodium Percentage (ESP) was observed in the studied salt-affected fields. ECe values decreased by 42% to 97%, while ESP values decreased by 13% to 94%. The observed decreases in ECe and ESP, coupled with an increase in pH, have been attributed to the invasion and establishment of Prosopis trees in the area. Similarly, the study by Shiferaw et al. (2021) has demonstrated that the invasion of land by Prosopis can lead to a notable increase in soil pH (by 1.5%) and a reduction in soil salinity and sodicity compared to non-invaded areas. However, large abandoned area still exhibits issues with salinity and/or sodicity, though their severity has decreased significantly compared to the earlier findings reported by Zeleke et al. (2014).

Table 5. Temporal Changes in Soil Chemistry of Salt-Affected Fields

Field No	Soil property Measurement in 2014 (Zeleke et al., 2014).			Soil property Measurement in 2021			Change in %		
	PH	Ece (dsm^{-1})	ESP (%)	PH	Ece (dsm^{-1})	ESP (%)	PH	Ece	ESP
Ka13	8.07	66.69	47.92	8.98	1.63	2.81	11.28	(97.56)	(94.14)
Ka14	8.0	39.62	36.2	7.96	22.68	31.43	(0.50)	(42.76)	(13.18)
Ka25	8.19	9.96	15.08	8.46	1.47	3.45	3.30	(85.24)	(77.12)

Note: ( ) indicate values are negative

Adapted to saline environments, *Prosopis juliflora* is a valuable resource in arid and semi-arid regions, providing fuel, timber, and fodder. While efforts to control its spread are ongoing, sustainable charcoal production offers a dual benefit: meeting bioenergy demands and clearing land for agriculture. Produced charcoal can be transported to highland areas and towns, while the resulting ash, potentially rich in salts, could be utilized in less salt-sensitive regions as a soil amendment.

Geo-statistical analysis of soil properties

Semivariogram models and best-fitted model parameters were given in Table 7 for the two soil depths. Spatial structure of soil properties was determined by analyzing semivariograms and selecting the best-fit model. The nugget values are very small, ranging from 0.00 to 0.11, indicating the spatial variability of soil properties. A nugget value of zero implies that the soil property of interest exhibits very high similarity at the smallest distances. In general, the spatial pattern was consistent with the depth of sampling. In the upper 0-30 cm soil depth the spatial variability of sand, silt, clay, and Ece were best described using exponential models, whereas pH, and ESP were best described using a spherical model except for CEC (Table 7). The fitted model type (Spherical or Exponential) indicates the nature of the spatial correlation. Spherical models suggest that the correlation decreases rapidly with distance and then stabilizes, while Exponential models suggest a gradual decrease in correlation. Soil properties exhibit moderate spatial class at both depths, except for CEC in the upper 0-30cm and clay in the lower 30-60cn that showed weak and strong spatial dependence, respectively. Moderate spatial dependence suggests that their values are influenced by factors that vary gradually across the area. These results are in agreement with those reported by Burgos et al. (2006) and Mousavifard et al. (2013). The effective spatial autocorrelation ranges show a large variation from 861 m for CEC up to 6,186 m for ESP.

The large range demonstrated that the observed values of a soil variable were influenced by other values for this variable over longer distances. Hence, a range of > 6000 m for ESP implies that these variable values had a stronger influence on nearby values than other soil variables at longer distances (Table 7). Spatial variability across distances less than the smallest separation distance between measurements is related to the nugget effect (Cemek et al. 2007; Webster, 1985). The substantial nugget effect suggests that additional sampling of these attributes at closer ranges and in bigger numbers may be required to discover spatial dependency, and a higher sample density will result in a more accurate map.

To assess the model's predictive accuracy, prediction error statistics were computed for all models (Table 7). Both the Mean Error (ME), which was generally close to zero, and the Root Mean Square Standardized Error (RMSSE), which was generally close to one, indicate that the model predictions exhibit low bias and reasonable accuracy. These findings are consistent with previous studies by Yeneneh et al. (2022), Some'e et al. (2011), and Mousavifard et al. (2013).

Table 6. Model parameters for soil variables to a depth of 0-30 cm and 30-60cm

Soil properties	Model type	Nugget (C0)	Partial sill (C)	Sill (C0 + C)	Nugget/sill ratio (%)	Spatial class	ME	RMSSE	Range (m)
Top 0 -30cm									
pH(−log [H⁺])	Spherical	0.0002	0.0003	0.0005	46.08	moderate	0.000	1.09	4,621
ECe (ds/m)	Exponential	0.072	0.078	0.149	47.95	moderate	0.003	1.03	3,287
CEC(meq/100g)	Spherical	0.007	0.002	0.009	78.08	weak	0.002	1.00	3,394
ESP (%)	Spherical	0.054	0.111	0.165	32.90	moderate	0.001	0.85	6,186
Sand (%)	Exponential	0.11	0.26	0.36	29.47	moderate	(0.17)	1.11	1,209
Silt (%)	Exponential	0.05	0.05	0.10	49.67	moderate	0.30	0.99	1,383
Clay (%)	Exponential	0.03	0.09	0.12	26.53	moderate	(0.12)	1.21	3,291
30-60									
pH(−log [H+])	Spherical	0.000	0.000	0.001	29.83	moderate	0.000	1.13	4,953
ECe(ds/m)	Exponential	0.079	0.094	0.173	45.78	moderate	0.003	1.06	3,262
CEC(meq/100g)	Exponential	0.004	0.002	0.006	65.96	moderate	0.002	1.01	861
ESP (%)	Spherical	0.032	0.079	0.111	29.11	moderate	0.002	0.97	3,927
Sand (%)	Exponential	0.11	0.26	0.36	29.47	moderate	(0.17)	1.11	1,209
Silt (%)	Exponential	0.05	0.05	0.10	49.67	moderate	0.30	0.99	1,383
Clay (%)	Spherical	0.03	0.13	0.16	21.10	Strong	(0.12)	1.20	4,459

*Notes: ME: Mean standard error; RMSSE: Estimated standardized mean of error of mean square root. Nugget/sill ratio (%) **Strong = % nugget <25%; moderate = % nugget 25–75%; random = % nugget >75%.*

Kriging of spatial variability of soil properties

Optimal kriging parameters were determine based on the results of the cross-validation procedure (Some'e et al., 2011; Mousavifard et al., 2013). Ordinary kriging techniques, along with variograms parameters were used to estimate the values of selected soil properties at unsampled locations within the study areas shown in Figure 5. The study area is characterized throughout by high textural variability, laterally with discontinuous fine silt and clay layers. The spatial distribution of silt content in the central parts of the study area, especially in the abandoned fields, is high to very high (Figure 5a). However, this figure shows that the fraction of the spatial distribution of the silt content decreases towards the eastern and western parts up to 20% to 30% silt content. The distribution pattern of clay content showed the opposite of silt. The high to highest clay contents (> 40%) occurred in large parts of the study area.

The pH was below 8 (slightly alkaline) and extended north-south, increasing in both easterly (moderately alkaline) and westward (moderately to strongly alkaline) directions (Figure 5c). The highest pH (>8.5) was in abandoned areas with high groundwater tables and invasions by Prosopis trees, and in long-irrigated areas in the northwestern periphery.

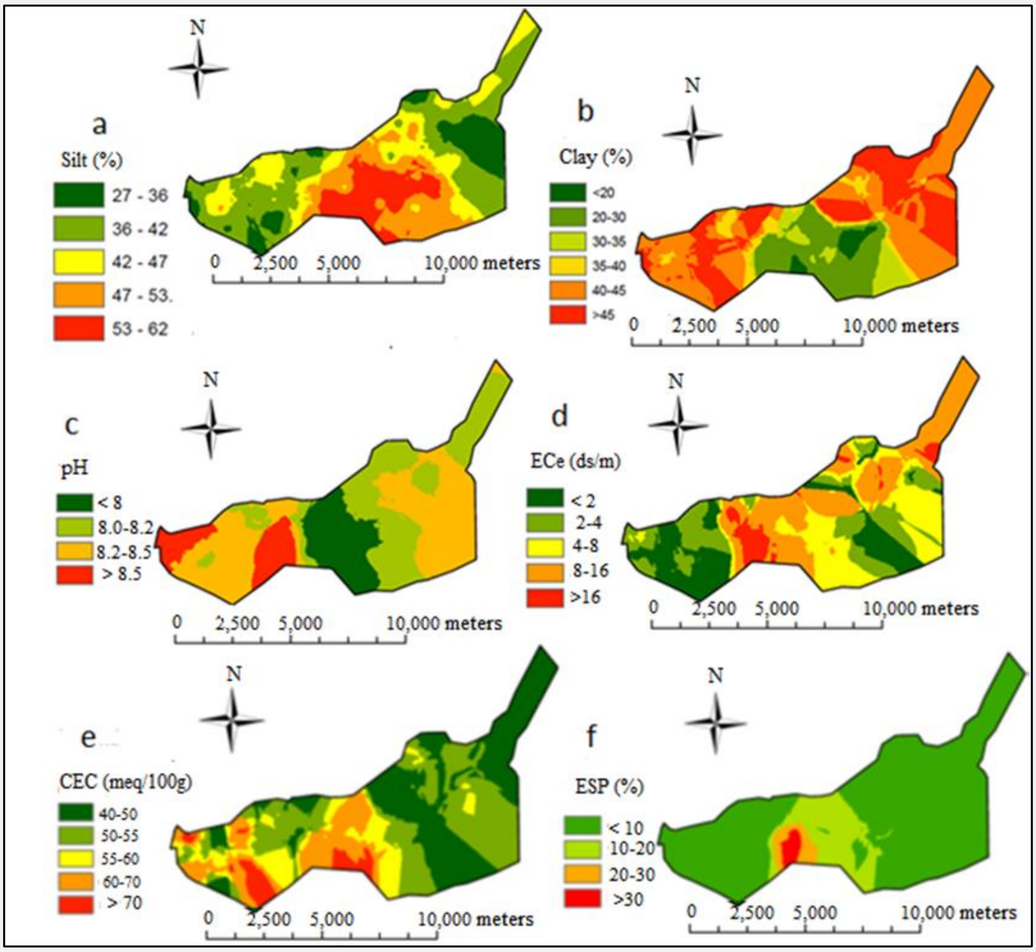

Figure 5. Interpolated maps of some selected soil properties using ordinary kriging.

The ECe was highest, exceeding 16 dsm^{-1} in spring areas where the soil contained less clay, resulting in a strongly saline class of salt-affected soils. Gradual decreases in ECe to the east resulted in slightly and moderately saline soil where it also decreased to 2-4 to less than 2 dsm^{-1} to the southeast. The irrigated section to the west had 2-4 to below 2 dsm^{-1}, giving the soil non-saline and alkaline classes.

Figure 5e shows that the highest level (>70 meq/100g) of soil CEC was located in the abandoned fields in the south-central and southwest, decreasing towards the east and north respectively. The distribution pattern of the ESP values is shown in Figure 5f. According to the pattern, ESP was low (<10%) in large parts of the studied areas and did not restrict normal plant growth except in some extremely sensitive plants such as deciduous fruit, avocado, cassava, and citrus (Landon, 1984). Similar to EC, the highest ESP (>30%) was also observed in southern central areas of abandoned fields where a shallow saline groundwater table is present.

CONCLUSION

This research provides valuable insights into the spatial distribution and variability of soil properties, enhancing our understanding of the local soil landscape. Soil textural analysis indicated a predominance of silt and clay fractions, suggesting recent formation of the parent materials. Furthermore, a soil assessment model effectively classified soil textural groups and identified four distinct salt classes: non-saline, saline, saline-sodic, and alkaline.

The spatial variability analysis of key soil properties within the study area revealed significant heterogeneity in most soil physico-chemical properties, characterized by moderate to strong spatial dependencies. Specifically, elevated levels of salinity and sodicity, exceeding acceptable thresholds, were observed in certain areas, suggesting a deterioration in soil quality.

The production of soil properties maps is the most important and the first step to identify susceptible areas for agriculture. In this regard, the kriging maps permit a graphical explanation of the area. By identifying important management issues and their potential causes, such as Prosopis juliflora invasion, absence proper drainage systems, quality of waters resources, this study lays the groundwork for informed soil management planning. However, further research is warranted to elucidate the relative importance of these factors in controlling the observed qualities of soil properties.

Ultimately, these findings can inform the development of optimal agricultural management practices within large-scale irrigated agricultural systems. Moreover, the successful application of this methodology in the resent study demonstrates its potential for implementation in other regions facing similar challenges.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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