Relationship Between Total Soluble Salts (TSS) and Ion Composition in Sodic Soils of the Karabakh Steppe: Implications for Ecosystem Services

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Abstract

Salinity, and particularly sodicity, represents one of the key constraints on agricultural productivity and the functioning of soil ecosystem services in the semi-arid regions of Azerbaijan, including the Karabakh Steppe of Azerbaijan. A reliable assessment of salinity conditions, together with ecosystem restoration and the design of effective reclamation strategies, requires a clear understanding of the relationships between total soluble salts (TSS), electrical conductivity (EC), and the concentrations of individual ions. In this study, the interactions between TSS and major ions were examined in sodic soils characterized by HCO_3^-–SO_4^{2-} and SO_4^{2-}–HCO_3^- salinity types. The analysis was based on detailed ion composition measurements and integrated soil profile investigations, covering both the plant root zone and the deeper vadose zone. The results indicate consistently strong correlations between TSS and EC throughout the soil profiles ($R > 0.8$). In contrast, the relationships between TSS and individual base ions showed greater variability, with correlation coefficients generally remaining below 0.90. This pattern suggests that ionic composition, rather than total salt concentration alone, plays a dominant role in regulating EC values. The salinity regime was defined by a cation dominance sequence of $Na^+ > Ca^{2+} > Mg^{2+}$, while the anion composition in both the root zone and vadose zone followed the order $HCO_3^- > SO_4^{2-} > Cl^-$. This distribution is typical of long-term irrigated sodic soils in semi-arid environments. Surface horizons exhibited moderately low selective EC; however, EC became increasingly variable with depth and reached maximum values below the root zone, particularly at depths of 100–150 cm. This vertical pattern reflects the downward leaching of salts from upper horizons driven by irrigation and precipitation, followed by their accumulation in deeper vadose layers under conditions of restricted drainage and upward capillary flux from shallow sodic groundwater. These results demonstrate that EC alone is insufficient to characterize sodicity hazards. Integrated evaluation of EC, TSS, ion composition, and depth-dependent processes provides a robust framework for salinity monitoring, soil reclamation, sustainable soil health, and ecosystem management in semi-arid irrigated systems.

Keywords: salinity, sodicity, soil solution, major ions ecosystem services, sustainable management

1. Introduction

1.1. Soil ecosystem services and salinity effects

Soil ecosystem services represent the fundamental functions through which soils sustain environmental quality, agricultural productivity, and human well-being. These services include regulating (water filtration, nutrient cycling, carbon sequestration, erosion control), supporting (soil formation, root anchorage, habitat provision), provisioning (food, fiber, biomass, clean water), and cultural services linked to landscapes and heritage (Figure 1). Together, they are commonly framed within the concepts of soil health and soil multi-functionality, which describe the ability of soils to deliver multiple services simultaneously (Keesstra et al., 2022). The One Health framework, soil ecosystem services link ecosystem integrity with animal and human health. Degradation under saline and sodic conditions thus constitutes not only an environmental constraint but also a wider public and animal health concern. Numerous studies show that soil salinity–solidity status, structure, organic matter content, and climatic stress strongly regulate ecosystem service delivery across agroecosystems (Adhikari & Bouma, 2021; Greiner et al., 2021; Lal, 2021; Schulte et al., 2021). Salinity-induced declines in aggregation, infiltration, microbial activity, and biogeochemical functioning reduce soil productivity and resilience, with indirect impacts on food security and livestock health (Dominati et al., 2010; Bünemann et al., 2018).

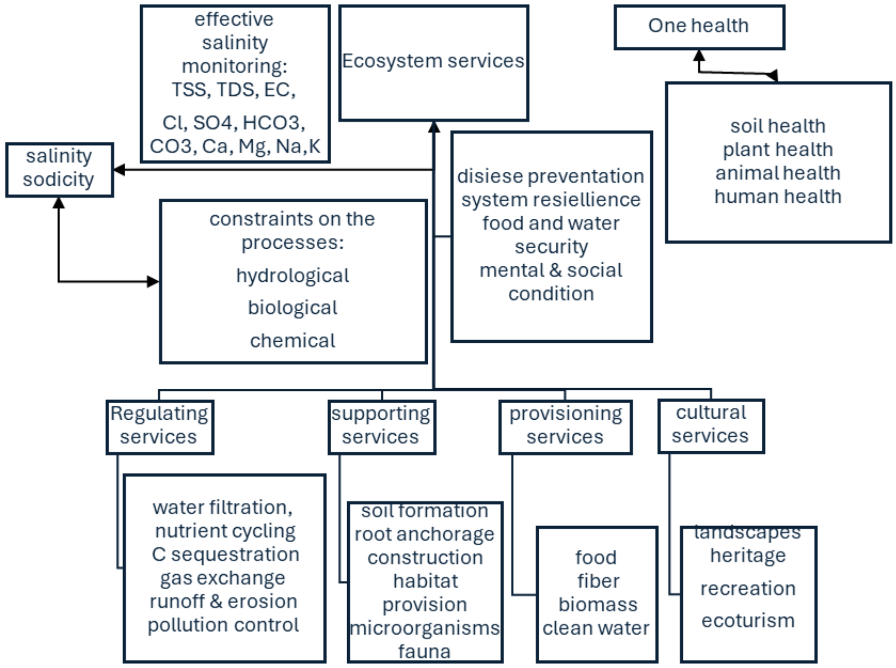


Figure 1. Soil ecosystem services and One Health interactions as affected by soil salinity-sodicity.

In semi-arid regions, soil health indicators also act as early-warning signals of sodicity-related One Health risks and are closely linked to key salinity metrics, including total soluble salts (TSS), total dissolved salts (TDS), electrical conductivity (EC), sodium adsorption ratio (SAR), and soluble ion composition (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-). Because interactions among TSS, EC, and ion composition control ion mobility, mineral equilibria, soil structure, and water flow, correct interpretation of TSS as a function of EC and ionic chemistry is essential for diagnosing salinity hazards and designing sustainable soil and ecosystem management strategies (Rengasamy, 2021; Corwin & Lesch, 2021; Qadir et al., 2021).

1.2. Main salt components of the soil solution

The behavior of soluble ions in soil solution is controlled by three complementary properties: ionic strength, ion-specific toxicity, and contribution to electrical conductivity (EC). Although often used interchangeably, these properties represent distinct chemical and biological processes with different implications for soil functioning and ecosystem services (Sposito, 2008).

Ionic strength is defined as $I=0.5\sum CiZi^2$. and depends on both ion concentration (C_i) and charge (Z_i). Thus, divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, CO_3^{2-}) contribute four times more to ionic strength than monovalent ions, exert an unreasonable influence on mineral equilibria, EC– SAR–ESP relationships, and clay coagulation-flocculation–dispersion behavior (Sposito, 2008; Sparks, 2020). Accordingly, the ionic-strength hierarchy generally follows: $CO_3^{2-} \approx$, $SO_4^{2-} \approx Ca^{2+} \approx$, $Mg^{2+} > Na^+ \approx K^+ \approx Cl^- \approx HCO_3^-$.

Ion toxicity, in contrast, reflects plant physiological and soil structural effects and typically follows the order: $Na^+ > Cl^- > HCO_3^- > CO_3^{2-} > Mg^{2+} > SO_4^{2-} > Ca^{2+} > K$ (Ayers & Westcot, 1985; Rengasamy, 2010). Sodium is particularly destructive due to its strong distributive effect on clay particles and disruption of plant nutrient balance, while Ca^{2+} reduces sodicity, also increasing soil structural stability (Qadir & Schubert, 2002).

Electrical conductivity (EC) is primarily dependent on mobility and dissociation, following the order of: $Cl^- > Na^+ > K^+ > Ca^{2+} > Mg^{2+} > SO_4^{2-} > HCO_3^- > CO_3^{2-}$ (Suarez, 1981; Rhoades et al., 1999). These contrasting hierarchies prove that sodicity hazards cannot be reliably diagnosed by EC or TSS alone, as similar EC values may correspond to considerable various structural and biological outcomes depending on ionic composition. Effective salinity–sodicity assessment, therefore, requires interpreting EC as a function of both TSS and ion-specific behavior, rather than relying on bulk salinity indicators alone (Rengasamy, 2010).

1.3. Factors affecting relationships among soil salinity components

Electrical conductivity (EC) reflects the combined effects of ionic strength and ion mobility and is commonly expressed as EC = f(TSS), because total soluble salts (TSS), together with major anions (Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}) and cations (Na^+, Ca^{2+}, Mg^{2+}, K^+), determine soil solution conductivity (Rengasamy, 2021). However, this relationship is not constant and varies with soil texture, chemistry, mineralogy, hydrological conditions, and management. (Figure 2) These factors regulate dissolution–precipitation reactions, ion exchange, permeability, leaching, and evaporation, making EC a system-dependent and often non-linear indicator rather than a simple proxy for TSS (Pereira et al., 2022; Wang et al., 2022).

EC–TSS–ion relationships are strongly impacted by management practices by changing salt redistribution and evaporative concentration (Figure 2). Practices such as, residue retention, mulching, and cover cropping help limit surface evaporation and stabilize EC, whereas poor drainage, soil compaction, and bare soil surfaces promote salt accumulation and elevate EC values. Introduction of gypsum or other Ca^{2+}-rich facilitates the replacement of exchangeable displaces Na^+, reduce ESP, enhances hydraulic conductivity, and makes EC–TDS relationships more predictable (Levy et al., 2005; Greiner et al., 2021).

Soil salt dynamics and the relations between electrical conductivity (EC), total soluble salts (TSS), and ion composition are also affected by tillage practices, irrigation water quality, and drainage conditions. Soil aggregates are destroyed by conventional tillage, which also increases surface evaporation, and creates favorable conditions for salt accumulation near the soil surface, as well as weakening the correspondence between EC and subsurface salinity (Richards, 1954; Levy et al., 2003; Mamedov & Levy, 2013). However, reduced or conservation tillage preserves soil structure, improving water filtration and percolation, as well as facilitates downward salt leaching, which leads to more consistent EC–TSS relationships and improved salinity regulation (Greiner et al., 2021; Zhang et al., 2022; FAO, 2015).

Soil salinity chemistry is adapted through the usage of saline or bicarbonate-rich irrigation water by applying Na^+, Cl^-, and SO_4^{2-} and carbonate precipitation reactions that reduce Ca^{2+} activity, which affect EC independently of bulk salt concentration (Ayers & Westcot, 1985; Suarez, 1981; Qadir & Schubert, 2002; Peker et al.,2024). This chemical dissociation unveils that soils with similar EC values may demonstrate completely different sodicity hazards and structural behavior (Levy et al., 2005; Rengasamy, 2010; Corwin & Yemoto, 2019).

Upward capillary flux in landscapes with shallow saline or sodic groundwater, further stimulates salt recycling into the root zone, which fosters Na dominance and increases salinity–sodicity risks under irrigated agriculture (Oster et al., 1999; Van der Zee et al., 2014; Cui et al., 2019; Oster et al., 2021; Li et al., 2023). These interacting management and hydrological controls confirm that EC–TSS–ion relationships are system-specific (Figure 2) and should be interpreted in the context of tillage intensity, irrigation water chemistry, drainage efficiency, and groundwater depth and chemistry (Corwin & Scudiero, 2017; Qadir et al., 2021; Rengasamy, 2021).

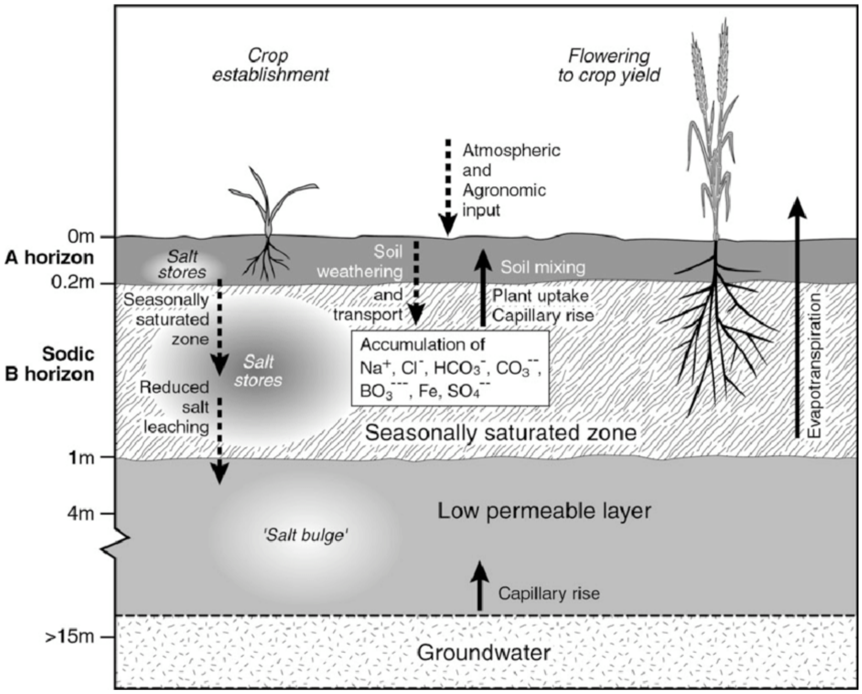


***Figure 2**. Accumulation of salts and ions in the root (vadose) zone driven by leaching–evaporation processes under shallow groundwater conditions*

Ion retention and mobility are also managed by soil texture and mineralogy. Fine-textured soils with high cation exchange capacity (CEC) retain cations on exchange sites, weakening EC–TSS proportionality, whereas coarse-textured soils favor dissolved salts and make EC a more reliable indicator. Carbonate and sulfate minerals regulate Ca^{2+} and Mg^{2+} availability and sodicity development, while smectitic clays amplify Na^{+}-induced dispersion and surface EC accumulation (Rengasamy, 2021; Mamedov & Levy, 2013).

The Objective. Together, these interacting physical, chemical, hydrological, and management factors demonstrate that EC–TSS relationships are site-specific rather than universal. Accordingly, the objective of this study is to quantify the relationships between TSS, EC, and individual ion concentrations in sodic soils of the Karabakh Steppe to improve salinity diagnosis and support sustainable soil management and ecosystem service delivery.

2. Materials and Methods

2.1. Study area and sampling

Soil samples were collected in spring from 60 locations within an irrigated collector–drainage system at the regional experimental station of the Research Institute of Water and Melioration in the Barda District, central Karabakh Plain, Azerbaijan (47°11′16.29″ E, 40°23′45.86″ N). Samples were taken from eight depth intervals (0–25 to 250–300 cm), and groundwater samples were collected from 40 sites at depths of 3.0–3.2 m.

The investigated area (30ha=300m x 600m +200 x 600m=18ha+12ha)) is equipped with the equipments for water balance measurement and with open drainage channels spaced 200 or 300 m apart (600 m lenght), with an average depth of ~3.0 m. Soils are long-term irrigated gray-meadow and meadow-gray soils (FAO Calcisols or LuvisolS) with clayey texture, low organic matter, and sodic groundwater chemistry (Ismayilov et al., 2021). Salinity levels are generally low to moderate (TSS < 0.10–0.2 g kg^{-1}), with dominant $Na–HCO_3–SO_4$ salinity types.

2.2. Soil and water analyses

Air-dried soil samples were ground and passed through a 2-mm sieve. Particle-size distribution was determined using the hydrometer method (Gee & Bauder, 1986). Cation exchange capacity (CEC), exchangeable sodium, calcium carbonate content, and soil organic matter were measured following standard procedures (e.g., ASA–SSSA, 1986; Nelson et al., 1982; Rhoades, 1986; Thomas, 1986). Within the crop layer (0–30 cm), soils exhibited considerable temporal variation in their key physicochemical properties. Beyond these temporal changes, significant differences were also apparent in soil composition, carbonate content, exchangeable sodium percentage (ESP), infiltration rates, aggregate stability, and levels of soil organic carbon (SOC). Although the surface soil was characterized by a clay texture, relatively low salinity levels, lower organic matter content, reduced aggregate stability, and lower infiltration rates, it was simultaneously distinguished by low saturated hydraulic conductivity, an alkaline reaction, elevated ESP, and high calcium carbonate content and higher field water retention (FC) and wilting point(WP)(Table 1).

Table 1. *Soil properties in the cultivated layer (0-30 cm)*

Soil	Particles, %		CEC[a]	pH	EC	OM	WSA	FC	WP	$CaCO_3$	ESP	K_S
	vlay	– sand	mmol/kg				------------------ % ---------------------					mm/h
Clay	54	18	42	8.4	1.7	1.4	50.4	28.2	19.1	16	14	1.2

CEC=cation exchange capacity; EC=electrical conductivity; OM=organic matter; FC=field capacity; wp=wilting point; ESP=exchange able sodium percentage; Ks=saturated hydraulic conductivity.

Soil salinity was assessed using 1:5 soil–water extracts, equilibrated for 4 h. EC and soluble ions were measured following standard methods (ASA–SSSA, 1986), and TSS was determined gravimetrically. Additional analyses included pH, saturation extract EC (ECe), soluble cations, carbonate and bicarbonate by titration, chloride by $AgNO_3$ titration, and SAR calculation. Also published EC–TSS relationships for sodic soils were used for comparison and salinity type evaluation (Ismayilov et al., 2021).

2.3. Statistical analysis

Statistical analyses were performed using SAS (PROC GLM, JMP). Mean comparisons were conducted using the Tukey–Kramer HSD test ($p < 0.05$). Pairwise correlations and least-squares regression and correlation analysis were applied to quantify relationships among EC, TSS, and individual ion concentrations (SAS Institute, 2018).

3. Results

3.1. Vertical distribution of salts in the soil profile

The vertical distribution of salts within the 0–300 cm soil profile shows clear depth-dependent patterns controlled by irrigation, drainage spacing, and shallow groundwater (~3 m). Under long-term management, salinity demonstrate heterogeneity, with distinct leaching and accumulation zones rather than a uniform vertical gradient. Electrical conductivity (EC) and total soluble salts (TSS) are generally lower in the upper layers but show increasing variability with depth, reaching maximum values occurring below the root zone (Figures3-4). This pattern designates downward salt transport from irrigation and rainfall, followed by partial accumulation in deeper vadose horizons because of restricted drainage and capillary rise (Figures 5-6).

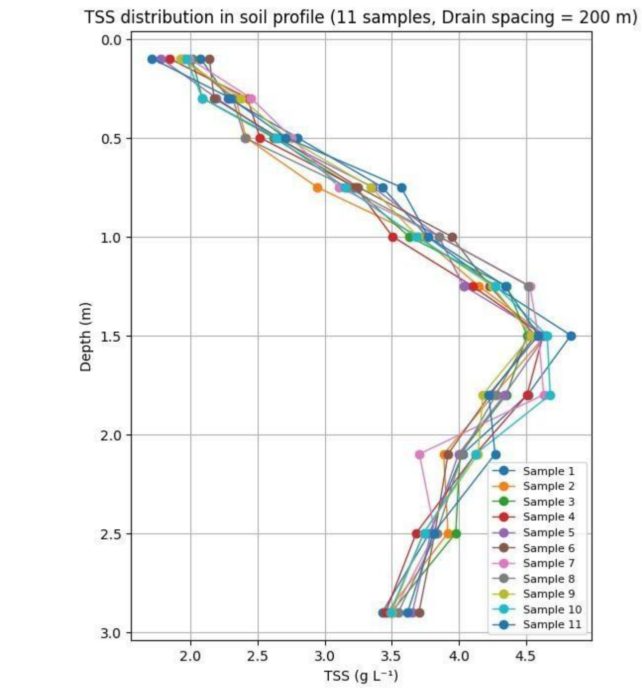


Figure 3. *Vertical distribution of total soluble salts (TSS) in a 0–3 m soil profile based on 11 sampling points under open drainage with 200 m spacing. Individual profiles consistently show low TSS in the root zone, a distinct accumulation zone at 1.5–2.0 m depth, and stabilization toward the rain/groundwater level, indicating effective salt leaching and controlled salinity under closer drain spacing.*

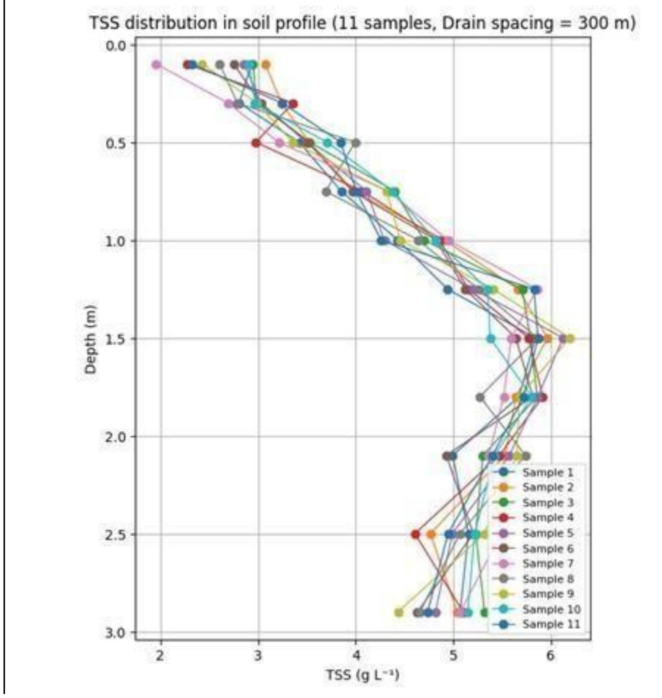


Figure 4. *Vertical distribution of total soluble salts (TSS) in a 0–3 m soil profile based on 11 sampling points under open drainage with 300 m spacing. Profiles show consistently higher TSS and a shallower accumulation zone (≈1.2–1.8 m) compared with closer drain spacing (200 m), indicating reduced leaching efficiency and enhanced salt storage in the vadose zone.*

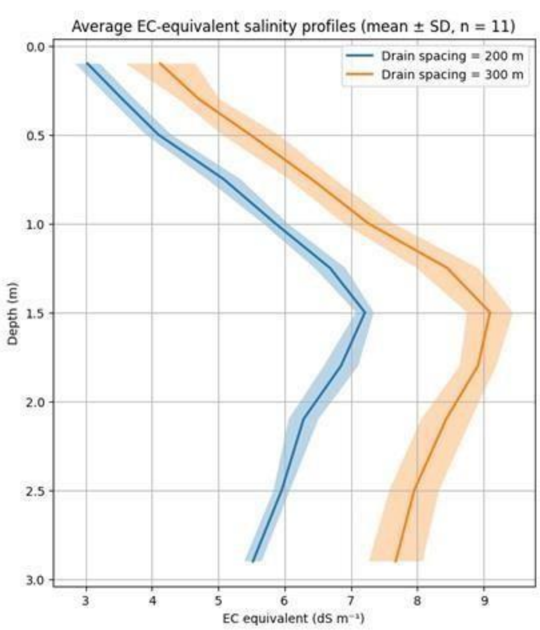


Figure 5. *Average EC-equivalent salinity profiles (mean ± standard deviation, n = 11) in a 0–3 m soil profile under open drainage with 200 m and 300 m spacing. EC values were derived from total soluble salts (TSS) using EC ≈ TSS/0.64. Narrower drain spacing (200 m) resulted in lower root-zone salinity and a deeper salinity maximum, whereas wider spacing (300 m) caused higher EC throughout the profile and a shallower accumulation zone with greater EC*

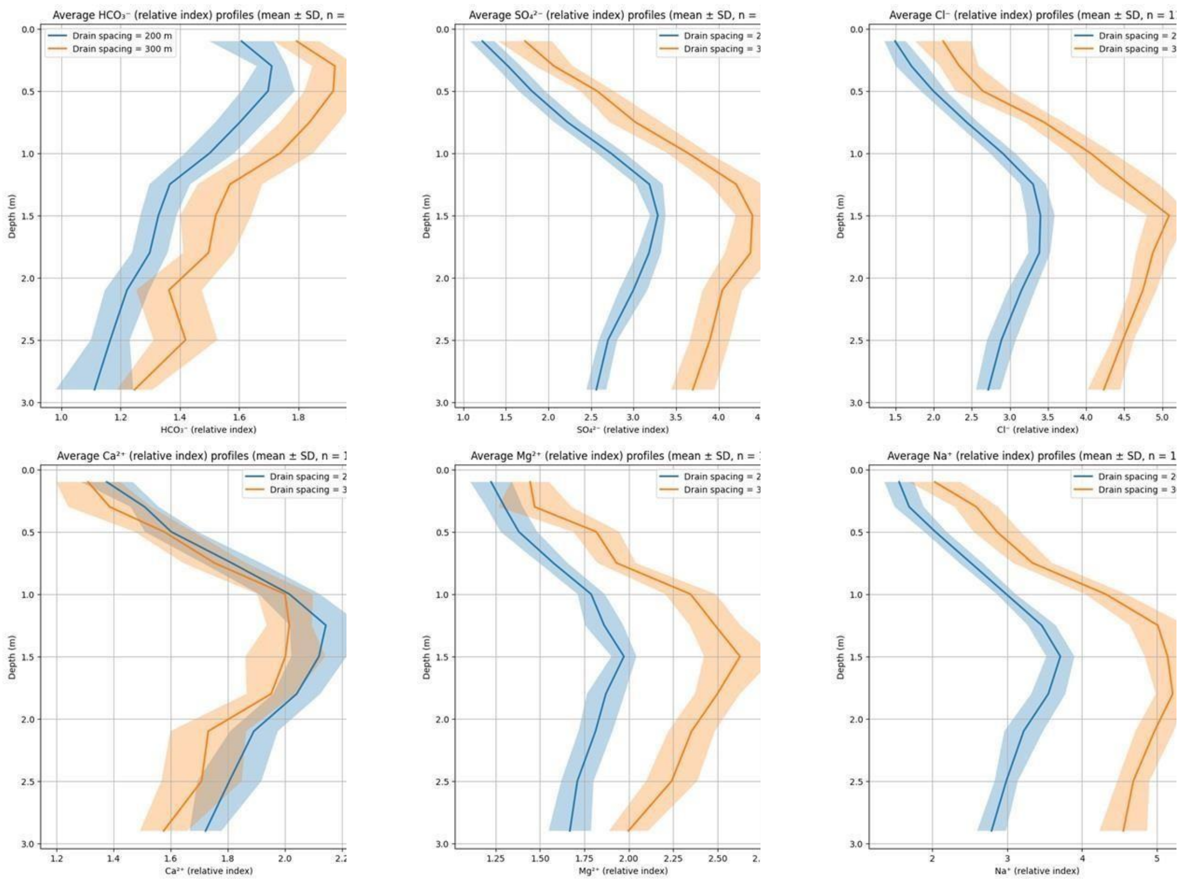


Figure 6*. Average depth profiles (mean ± SD, n = 11) of ions in a 0–3 m soil profile under open drainage with 200 m and 300 m spacing. Shaded bands represent ±1 SD across sampling points, indicating spatial variability. Wider drain spacing results in higher ion accumulation and shallower maxima, which correspond to reduced leaching efficiency*.

HCO_3^- and SO_4^{2-} manage ionic composition throughout the profile, reaffirming an HCO_3–SO_4 salinity type. Bicarbonate demonstrates high variability and positive skewness, which indicate carbonate dissolution and alkalinity development. In contrast, sulfate exhibits the simultaneous influence during leaching and precipitation–dissolution processes within the soil profile. Chloride, as a relatively conservative ion, shows the clearest tendency toward deep accumulation, indicating zones of long-term salt storage. Sodium is present throughout the entire profile with moderate average concentrations but marked variability, suggesting that sodicity-related processes are not confined to the root zone and instead extend downward through cation exchange and vertical redistribution. By comparison, Ca^{2+} and Mg^{2+} maintain relatively stable distributions with depth. Overall, the soil profile can be described as dynamically restructured, with active salt redistribution in surface horizons, partial leaching across the root zone, and the accumulation of soluble salts in deeper layers. This vertical differentiation highlights the importance of assessing the full soil profile, rather than only surface horizons, when evaluating salinity status and drainage efficiency.

3.2. Descriptive statistics of salinity components

The descriptive statistics show clear depth-dependent changes in hydrochemical properties, with the 0–300 cm profile consistently exhibiting higher variability and slightly elevated concentrations compared to the shallow 0–100 cm zone (Table 2). EC increased with depth, from a mean of 0.386 dS m^{-1} (0–100 cm) to 0.462 dS m^{-1} (0–300 cm). The maximum value also rose markedly, indicating progressive salt accumulation in deeper layers. Higher standard deviation in the deeper profile suggests more heterogeneous salinity distribution.

a) 0-100 root zone										
No.	**Component**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Variance**	**Skewness**	**Kurtosis**	**N**
1	EC (dS m^{-1})	0.155	1.634	0.386	0.288	0.265	0.071	2.79	8.97	88
2	TSS	0.058	0.648	0.143	0.106	0.1	0.01	2.96	9.98	88
3	Na^{+}	−0.004	0.13	0.024	0.015	0.025	0.001	1.65	3.24	88
4	Ca^{2+}	0	0.03	0.008	0.007	0.006	0.0	0.89	1.21	88
5	Mg^{2+}	0	0.03	0.006	0.006	0.006	0.0	2.36	7	88
6	Cl^{-}	0	0.053	0.011	0.008	0.008	0.0	2.8	9.84	88
7	SO_4^{2-}	0	0.067	0.019	0.01	0.017	0.0	1.28	0.75	88
8	HCO_3^{-}	0	0.445	0.071	0.049	0.068	0.005	3.64	14.65	88
9	CO_3^{2-}	0	0.02	0.003	0.002	0.004	0.0	2.33	7.26	88
b)0-300 cm vadose zone										
No.	**Component**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Variance**	**Skewness**	**Kurtosis**	**N**
1	EC (dS m^{-1})	0.155	2.32	0.462	0.288	0.366	0.134	2.43	6.99	176
2	TSS	0.058	0.684	0.168	0.128	0.121	0.015	2.68	8.28	176
3	Na^{+}	−0.011	0.13	0.022	0.015	0.022	0.0	1.61	3.13	176
4	Ca^{2+}	0	0.035	0.008	0.006	0.006	0.0	0.96	1.55	176
5	Mg^{2+}	0	0.033	0.005	0.005	0.005	0.0	2.72	9.6	176
6	Cl^{-}	0	0.151	0.012	0.008	0.015	0.0	5.82	44.24	176
7	SO_4^{2-}	0	0.096	0.017	0.01	0.016	0.0	1.88	4.29	176
8	HCO_3^{-}	0	0.445	0.062	0.049	0.054	0.0	4.39	23.24	176
9	CO_3^{2-}	0	0.02	0.002	0	0.003	0.0	2.57	9.67	176

TSS showed a slight increase with depth. Both zones displayed strong positive skewness and high kurtosis, indicating occasional high-pulse transport events rather than uniform distribution. Overall, the 0–300 cm vadose zone is more heterogeneous and chemically variable than the 0–100 cm zone. The pattern suggests that deep vadose zone processes are dominated by uneven solute transport, possible preferential flow paths, and localized salt accumulation zones, while the shallow zone reflects more moderate and relatively stable conditions (Table 2).

The domination of HCO_3^{-} and Na^{+} within 0–100 cm reflects the combined influence of irrigation water chemistry and partial salt recycling from deeper horizons. However, compared with the 0–300 cm profile, the reduced maxima and variances for most ions indicate that active leaching and crop water uptake limit salt accumulation in the upper soil layers. The systematic difference between mean and median values in the root zone confirms that crop-experienced salinity is not adequately captured by mean concentrations alone. Osmotic or sodicity stress may intermittently be imposed by localized salt hotspots within the root zone,

Salinity statistics for the vadose zone (0–300 cm) present a highly heterogeneous and nonequilibrium system: analysis of the full profile indicates that most ions possess positive skewness and elevated kurtosis, suggesting that salts accumulate in localized zones instead of forming uniform vertical gradients. Throughout the profile, we observe that the main contributors to salinity are bicarbonate (HCO_3^{-}) and sodium (Na^{+}). Persistent differences between mean and median values, together with large variances, point to episodic salt enrichment resulting from the combined action of downward leaching and upward capillary rise from shallow groundwater. Elevated kurtosis values for HCO_3^{-}, Cl^{-}, Na^{+}, and total soluble salts further suggest that salt-enriched layers develop within horizons that otherwise display moderate salinity levels.

At the scale of the entire 0–300 cm profile, these patterns illustrate how multiple processes interact over time. Irrigation-induced leaching, evaporation, groundwater chemistry, and drainage efficiency jointly shape the vertical distribution of salts. As a result, the full profile provides insight into long-term salinity dynamics rather than reflecting only short-term conditions within the root zone. A comparison between the two depth intervals (0–100 cm and 0–300 cm) reveals a clear functional contrast. The upper 0–100 cm primarily captures short- to medium-term salinity conditions and is strongly influenced by irrigation practices, precipitation, and crop water uptake. In contrast, the deeper 0–300 cm profile reflects long-term salt storage and redistribution. Salts tend to accumulate in deeper layers, which can act as a reservoir, releasing salts back toward the root zone through capillary rise during dry periods or under limited leaching conditions.

Ecosystem service–based general clarification: The measured salinity, sodicity, and soil property indicators directly reflect how well the ecosystem is functioning. Close drainage spacing helps control salinity and sodicity, which supports soil structure and nutrient retention, and in turn improves crop productivity and water-use efficiency (Table 2). These results show that looking only at the root zone may underestimate long-term salinity and sodicity risks. While the 0–100 cm layer may seem moderately saline under current management, the full 0–300 cm profile shows that significant salts are stored deeper in the soil, which can affect soil quality over time. Therefore, effective salinity management needs strategies that consider both the root zone and the interactions with deeper soil layers and groundwater.

3.3. Correlation between salt components

The analysis of soil salinity components revealed clear and meaningful relationships among salinity parameters and major ions across the soil profile. Total soluble solids (TSS) showed a strong positive correlation with electrical conductivity (EC), confirming that dissolved salts are the main contributors to salinity and supporting the use of EC as a reliable indicator of soil salinity intensity (Table 3).

Table3. *Pairwise correlation coefficients ® between EC, TSS, and major ions. Pearson correlation coefficients (significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001).*

Variables	EC	TSS	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}
EC	1	0.93***	0.74***	0.21**	0.56***	0.35***	0.26***	0.84***	0.47***
TSS	0.93***	1	0.85***	0.14	0.52***	0.33***	0.30***	0.90***	0.55***
Na^+	0.74***	0.85***	1	−0.21**	0.12	0.37***	0.33***	0.72***	0.49***
Ca^{2+}	0.21**	0.14	−0.21**	1	0.28***	0.14	0.08	0.15*	−0.03
Mg^{2+}	0.56***	0.52***	0.12	0.28***	1	0.22**	0.09	0.55***	0.35***
Cl^-	0.35***	0.33***	0.37***	0.14	0.22**	1	0.02	0.06	0.04
SO_4^{2-}	0.26***	0.30***	0.33***	0.08	0.09	0.02	1	0.05	−0.01
HCO_3^-	0.84***	0.90***	0.72***	0.15*	0.55***	0.06	0.05	1	0.57***
CO_3^{2-}	0.47***	0.55***	0.49***	−0.03	0.35***	0.04	−0.01	0.57***	1

Sodium (Na^+) showed strong positive correlations with chloride (Cl^-) and sulfate (SO_4^{2-}), indicating that salinity is mainly controlled by neutral sodium salts rather than carbonate-dominated systems. This pattern is typical in irrigated semi-arid areas influenced by irrigation return flow and shallow groundwater, where evaporation and limited leaching favor the accumulation of Na–Cl and Na–SO_4 salts. The strong relationships among these ions suggest they share a common source and undergo coupled transport and accumulation processes within the vadose zone (Table3).

By contrast, carbonate species (CO_3^{2-} and HCO_3^-) exhibited weak to negative correlations with calcium (Ca^{2+}) and magnesium (Mg^{2+}). This inverse association is consistent with carbonate precipitation processes, which lower the concentrations of dissolved Ca^{2+} and Mg^{2+} and progressively shift the ionic balance toward sodium (Na^+) dominance. As a consequence, the potential for sodicity increases, since the reduced availability of divalent cations limits their ability to mitigate the structural effects of exchangeable sodium in the soil. Negative correlations between Na^+ and Ca^{2+}/Mg^{2+} further indicate that cation exchange is occurring, with sodium gradually replacing Ca and Mg on soil exchange sites. This pattern is consistent with the structural degradation often seen in sodic and saline–sodic soils.

Conversely, Ca^{2+} and Mg^{2+} are closely correlated with each other, suggesting a common geochemical source and similar mobility within the soil profile. Overall, these correlations show that soil salinity is mainly controlled by neutral sodium salts, while reductions in Ca^{2+} and Mg^{2+} due to carbonates indirectly promote sodicity. These interactions highlight the combined influence of salinity chemistry, drainage efficiency, and ion exchange processes on soil chemical degradation under semi-arid irrigated conditions.

3.4. Linear relationship between salt components

Results of linear relationships between EC (TSS) and ion components (0-300 cm) are given in Table 4 and Figure 7. From an ecosystem point of view, groundwater at ~3 m depth showed clear differences in sodicity hazard between drainage spacing, while total salinity remained comparable.

Table 4. *Linear relationships between EC and ion components (TSS, Na, Ca, Mg, Cl, SO_4, CO_3, HCO_3)*

No.	Independent variable (X)	Intercept, *a*	Slope, *b*	R^2	*p*-value	Interpretation
1	TSS	0.029	2.521	0.868	***	EC is strongly controlled by TSSs
2	Na^+	0.192	7.542	0.55	***	Sodium is a dominant driver of EC under sodic conditions
3	HCO_3^-	0.139	3.522	0.706	***	Strong alkaline control on EC
4	CO_3^{2-}	0.289	34.038	0.223	***	Secondary effect linked to alkalinity
5	Mg^{2+}	0.234	23.431	0.312	***	Moderate contribution, buffered by precipitation/exchange
6	Cl^-	0.296	5.292	0.123	***	Conservative ion with limited EC control
7	SO_4^{2-}	0.295	3.712	0.069	**	Minor contribution to EC variability
8	Ca^{2+}	0.295	8.25	0.046	**	Weak effect due to carbonate buffering

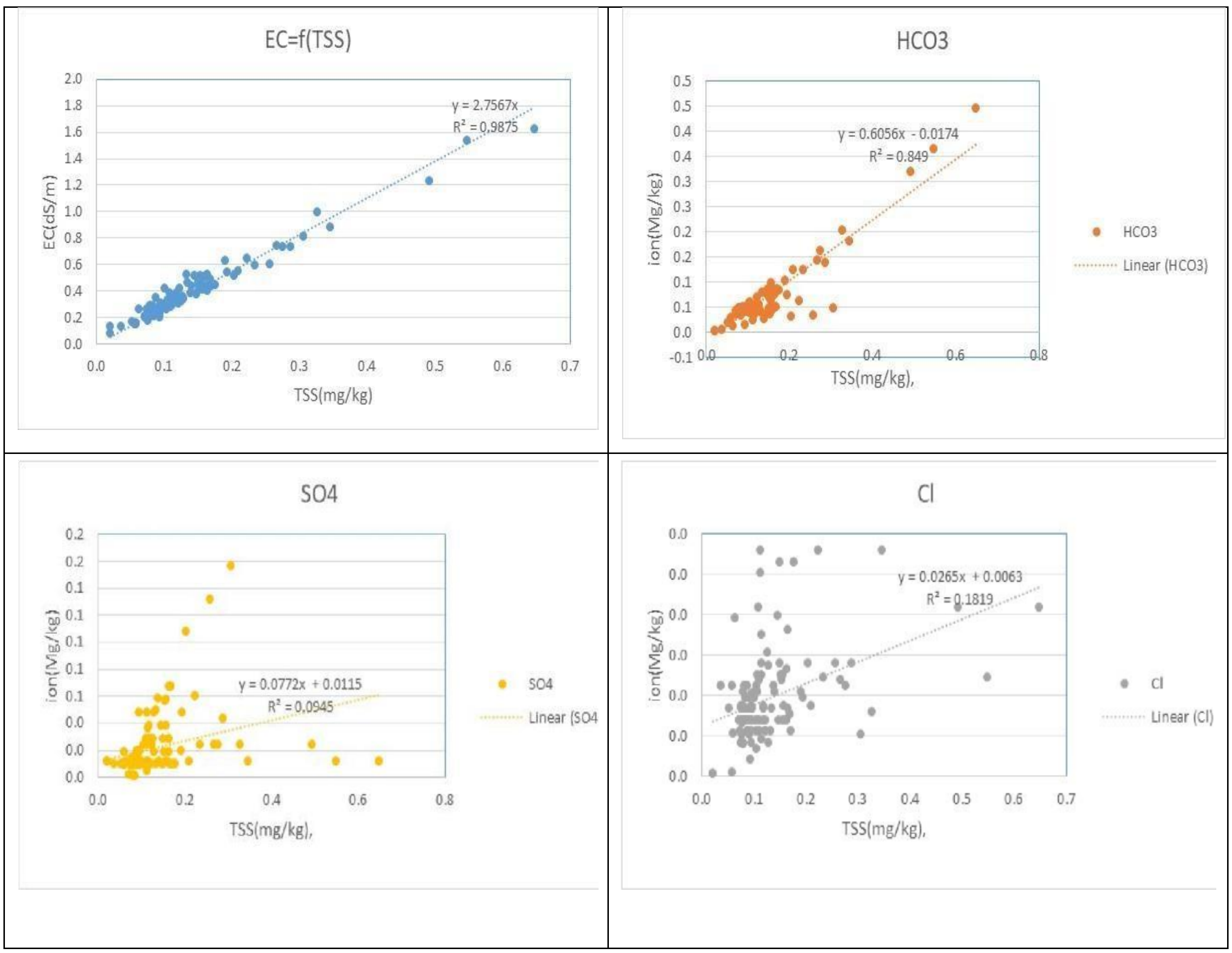
Drainage 200 m (D200): Groundwater was moderately saline with lower Na^+ dominance and lower SAR, indicating a reduced sodicity risk. $Ca^{2+} + Mg^{2+}$ activity was relatively higher, buffering Na^+ effects. For drainage, 300 m groundwater exhibited higher Na^+ concentrations and higher SAR, despite similar TSS. This indicates a shift toward sodic or saline–sodic groundwater, increasing the dispersion hazard for overlying soils. Overall, widening drainage spacing increased groundwater sodicity more strongly than groundwater salinity (Figures 3-6).

Salinity component as a function of groundwater chemistry and drainage spacing: From an ecosystem point of view, groundwater at ~3 m depth showed clear differences in sodicity hazard between drainage spacing, while total salinity remained comparable. Drainage 200 m (D200): Groundwater was moderately saline with lower Na^+ dominance and lower SAR, indicating a reduced sodicity risk. $Ca^{2+} + Mg^{2+}$ activity was relatively higher, buffering Na^+ effects. For drainage, 300 m groundwater exhibited higher Na^+ concentrations and higher SAR, despite similar TSS. This indicates a shift toward sodic or saline– sodic groundwater, increasing the dispersion hazard for overlying soils. Overall, widening drainage spacing increased groundwater sodicity more strongly than groundwater salinity (**Figures 3-6; Table 2**). D200 profiles showed lower overall TSS, a deeper displacement of salts, and weaker Na^+ accumulation in the root zone. D300 profiles retained higher salt loads throughout the profile and showed stronger Na^+ dominance, consistent with reduced drainage efficiency and enhanced groundwater feedback. Drainage spacing controlled the direction of salt flux: net downward export under D200 versus partial recycling under D300(Figure 3-6).

Interaction of irrigation and rainfall with soil salinity: Fresh irrigation water and rainfall reduced surface salinity episodically but did not eliminate subsurface salt accumulation. Under D300, dilution of soil solution electrolytes during wetting events enhanced Na-induced dispersion, counteracting leaching benefits. Under D200, similar water inputs resulted in net salt removal, indicating that water quality benefits depended strongly on drainage efficiency.

Spatial role of saline–sodic spots within drained fields: Distinct saline–sodic spots (patches/hotspots) were consistently observed within the drained fields, particularly under 300 m drainage spacing (D300). These zones had a strong influence on both vertical salt movement and groundwater chemistry, showing higher evaporative concentration and accumulation of conservative anions. Carbonate precipitation reduced Ca^{2+} activity, which reinforced sodicity. As a result, these zones acted as local sources of saline–sodic groundwater recharge.

Salinity type and land-use response: Across all crops (cotton, maize, wheat, alfalfa), the dominant soil salinity types followed a consistent depth sequence: Na–HCO_3 (surface) → Na–(HCO_3–SO_4/Cl) (midprofile) → Na–Cl / Na–SO_4 (deep profile and groundwater). Cotton showed higher tolerance to salinity but remained sensitive to sodicity-driven structural decline. Maize and wheat were most affected during establishment under sodic surface conditions. Alfalfa improved soil physical conditions locally but did not prevent salinity–sodicity persistence under D300, and it led to the relationship between EC and ion components (Figure 7).



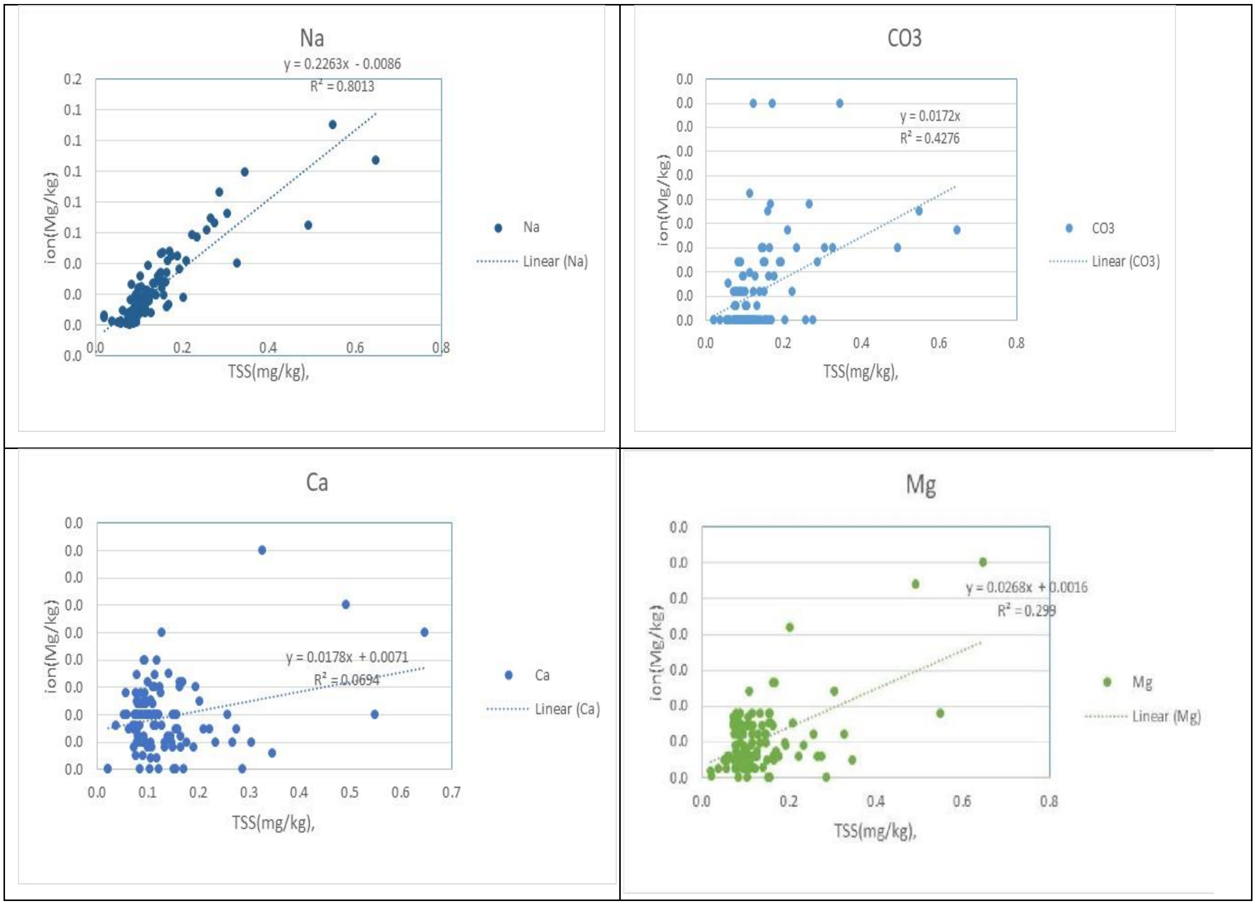


Figure 7. *Linear relationship between the TSS and ion components*

Crop Response Within Saline–Sodic Spots. Cotton showed some tolerance to high EC, but emergence was affected, and root aeration was reduced within these saline–sodic patches. Maize and wheat experienced strong yield penalties due to surface crusting and early-season sodicity stress. Alfalfa stands were patchy; while roots penetrated deeper, plant vigor declined where sodicity restricted water movement. Yield variability across fields was therefore largely explained by the presence and intensity of saline–sodic spots, rather than mean field salinity.

Short summary of key results: Groundwater sodicity increased markedly when drainage spacing widened from 200 to 300 m. Maximum salt accumulation occurred at 25–150 cm depth, regardless of crop. Drainage spacing, rather than irrigation amount alone, determined whether salts were exported or recycled. Salinity type evolved systematically with depth from alkaline sodic to saline–sodic systems. These results demonstrate that sodic groundwater–soil coupling is the dominant control on salinity and sodicity dynamics in semi-arid irrigated soils.

During irrigation and rainfall events, saline–sodic patches behaved like hydraulic bottlenecks. Clay dispersion slowed water infiltration, causing slower percolation compared with the surrounding soils. This led to salt accumulation mainly in the mid-profile (25–150 cm) beneath these spots, amplifying the salt bulge. During dry periods, upward capillary flow from shallow groundwater brought Na-rich salts back into the deeper vadose zone under the same locations, creating a self-reinforcing feedback loop.

4. Discussion

4.1. Depth-dependent salinity dynamics and drainage control

The results demonstrate that salinity and sodicity in the Karabakh Steppe are strongly depthdependent and fundamentally controlled by drainage spacing and shallow sodic groundwater. Lower EC and TSS in the upper soil layers, combined with increasing variability and maxima below the root zone (100–150 cm), indicate effective downward salt transport driven by irrigation and rainfall, followed by retention and accumulation in deeper vadose horizons. This behavior is characteristic of long-term irrigated semi-arid systems with shallow groundwater influence (Richards, 1954; Tanji & Wallender, 2011; Corwin & Scudiero, 2017).

Closer drain spacing (200 m) promoted deeper displacement of salts and reduced salt storage within the effective rooting zone, whereas wider spacing (300 m) resulted in shallower accumulation zones and higher overall salt loads throughout the profile. Similar drainage-controlled vertical salinity patterns have been documented in irrigated sodic soils worldwide, where reduced drain spacing increases net salt export and limits salt recycling via capillary rise (Skaggs & van Schilfgaarde, 1999; Oster et al., 1999; Qadir et al., 2021).

4.2. Salinity chemistry and sodicity development

Across both depth intervals, salinity chemistry was dominated by Na^+ and HCO_3^-–SO_4^{2-} systems, consistent with bicarbonate-rich irrigation return flows and sodic groundwater chemistry typical of semiarid irrigated landscapes (Ayers & Westcot, 1985; Rengasamy, 2006, 2021). Strong correlations between EC, TSS, Na^+, and HCO_3^- confirm that bulk salinity is largely governed by sodic–alkaline salts rather than by chloride-dominated systems alone (Suarez, 1981; Sharma & Singh, 2020; Yu et al., 2023).

The weak or negative relationships between Na^+ and Ca^{2+}, together with limited correlations between EC and divalent cations, highlight the role of cation exchange and carbonate precipitation in sodicity development (Bower, 1959; Suarez, 1981; Qadir & Schubert, 2002). Carbonate precipitation lowers Ca^{2+} activity in solution, indirectly increasing Na^+ dominance and encouraging clay dispersion, decreased permeability, and structural instability (Rengasamy, 2010; Levy et al., 2005). Due to this mechanism, it is possible to explain why soils with similar EC values may vary significantly in physical behavior and ecosystem functioning.

4.3. Root-zone versus vadose zone salinity

Descriptive statistics distinctly separate the root zone (0–100 cm) from the full vadose zone (0–300 cm). Although mean salinity within the root zone was relatively low, pronounced positive skewness and elevated kurtosis indicate heterogeneous salt distributions and the occurrence of localized saline–sodic hotspots. Such hotspots may subject crops to episodic osmotic or sodicity stress, even when average salinity appears moderate (Corwin & Lesch, 2005; Lesch et al., 1992; Corwin & Kaffka, 2015).

The 0–300 cm soil profile reflects long-term salt storage and redistribution, showing the overall salinity balance of the soil–groundwater system rather than just short-term management effects (Van der Zee et al., 2014; Corwin & Scudiero, 2017). This highlights that evaluations limited to the root zone may underestimate long-term salinity and sodicity risks in irrigated systems.

Sodic groundwater and bicarbonate-rich irrigation water play a central role in shaping soil chemical conditions, with direct implications for structural stability and hydraulic functioning in semi-arid, calcareous agroecosystems. Variations in sodic water chemistry—particularly elevated bicarbonate or sodium concentrations—alter soil solution processes by influencing Na^+ activity, Ca^{2+} availability, and carbonate precipitation–dissolution dynamics. These shifts promote increases in exchangeable sodium percentage (ESP) and electrical conductivity (EC), both of which are indirectly linked to total soluble salts (Peker et al., 2024). Such chemical modifications exert a strong control on soil physical behavior. Under sodicconditions, soil aggregates become increasingly prone to slaking as Na^+ dominance and reduced electrolyte concentrations weaken inter-particle bonding. As a result, soil structure, including saturated hydraulic conductivity, becomes highly sensitive to irrigation water quality and ionic composition (Levy et al., 2003). This structural vulnerability is further amplified during wetting events, when the combined effects of salinity, sodicity, and wetting rate trigger clay swelling, aggregate disintegration, and marked declines in saturated hydraulic conductivity (Levy et al., 2005).

At a finer scale, sodicity-related degradation is evident in near-saturation water retention behavior. Measurements at low suctions reveal the susceptibility of soil pore systems to deformation and collapse, processes that can precede irreversible reductions in infiltration capacity and permeability (Levy & Mamedov, 2013).

Taken together, these findings indicate that patterns in EC, total soluble salts, and ion relationships in sodic soils arise from the coupled action of chemical and physical processes rather than from salt concentration alone. This underscores the need to account for irrigation water chemistry, wetting dynamics, and indicators of structural integrity when evaluating salinity and sodicity risks in irrigated semi-arid environments.

4.4. Saline–sodic hotspots and feedback mechanisms

Saline–sodic hotspots experienced particularly under wider drainage spacing produce a disproportionate influence on both vertical salt redistribution and groundwater chemistry. decreased infiltration and hydraulic conductivity within these zones delay leaching, while increasing evaporative concentration, supporting Na-induced dispersion and salt accumulation at mid-profile depths (Rengasamy, 2006, 2010; Van der Zee et al., 2014).

These hotspots act as localized sources of saline–sodic groundwater recharge and establish selfreinforcing feedback loops, whereas soil structural degradation reduces reclamation efficiency and preserves sodicity over time (Oster et al., 1999; Qadir & Schubert, 2002). Irrigated fields often demonstrated similar patch-dominated salinity behavior, where a small fraction of the landscape controls much of the salinity hazard and yield variability (Corwin & Lesch, 2005; Corwin & Scudiero, 2017).

4.5. Implications for ecosystem services and management

From the perspective of ecosystem services, how drainage spacing acts as a critical in managing several functions at once. When drains are placed closer together, they help manage salt and sodium buildup (regulating services), increase soil structure and water movement (supporting services), and maintain steady crop yields and efficient water use (provisioning services) (Dominati et al., 2010; Greiner et al., 2021; Keesstra et al., 2022). In contrast, wider drainage spacing may reduce short-term infrastructure costs, but it can increase long-term salt accumulation, soil degradation, and yield instability, which ultimately affects soil multifunctionality and land sustainability (Adhikari & Bouma, 2021; Lal, 2021; Qadir et al., 2021). These findings demonstrate that commonly used soil salinity indicators—such as electrical conductivity (EC), total soluble salts (TSS), and ionic composition—extend beyond their role as purely agronomic metrics. They also provide insight into how effectively soil-based ecosystem services operate within irrigated semi-arid environments.

5.Conclusion

This study provides an integrated assessment of soil salinity and sodicity in the Karabakh Steppe, indicating that their spatial and vertical dynamics are primarily governed by drainage spacing, shallow sodic groundwater, and the composition of dissolved salts, rather than by total salinity levels alone. Soil profile investigations extending to a depth of 3 m reveal that EC and TSS values are generally lower within the root zone, whereas greater variability and distinct accumulation peaks occur at depths of approximately

100–150 cm. This suggests that irrigation and rainfall move salts downward, but some remain or rise in deeper layers when drainage is limited and capillary rise occurs from sodic groundwater.

Strong links between EC, TSS, Na^+, and HCO_3^- indicate that sodic–alkaline salts mainly control salinity. In contrast, relationships between EC and Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} are weaker due to carbonate buffering, cation exchange, and stable ion behavior. As a result, soils with similar EC values can have very different sodicity risks and structural responses, showing that EC alone is not enough to assess soil degradation in semi-arid irrigated areas.

Drainage spacing has a significant influence on both soil and groundwater chemistry. Closer spacing (e.g., 200 m) facilitates the downward movement of salts, mitigates Na^+ dominance, lowers sodicity risk, and enhances overall salinity management throughout the soil profile. In contrast, wider spacing (e.g., 300 m) can lead to increased groundwater sodicity, accumulation of salts at intermediate depths, and reinforced interactions among saline–sodic hotspots, restricted infiltration, and upward salt movement. These localized hotspots largely account for observed soil heterogeneity, crop stress, and yield instability, even when average salinity levels appear moderate.

From an ecosystem standpoint, soil salinity indicators—such as EC, TSS, and ion composition—reflect regulating, supporting, and provisioning functions. Strategically designed drainage systems contribute to improved salinity management, better soil structure, enhanced water movement, effective nutrient retention, and increased crop productivity. Conversely, inadequate drainage may progressively degrade soil quality and compromise long-term sustainability. Evaluating only the root zone can underestimate total salt storage and future risks, making a full-profile assessment crucial.

Sustainable management of semi-arid irrigated soils requires an integrated consideration of EC, TSS, ion composition, depth-dependent processes, groundwater chemistry, and drainage layout. Monitoring the entire soil profile allows early identification of salinity–sodicity hotspots and supports adaptive management at both field and landscape scales, thereby promoting soil reclamation, ecosystem resilience, and long-term land sustainability.

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