

Assessment of agricultural land salinization via soil analysis and remote sensing data: Case study in Pavlodar region, Kazakhstan

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Abstract: Soil salinization is one of the most widespread soil degradation processes, especially in arid and semi-arid regions. In such climatic conditions, soluble salts accumulate in the soil, leading to deterioration in soil properties and ultimately reduced crop yield. The purpose of this study was to analyse the relationship between the level of soil salinity and the main spectral indicators obtained from Landsat satellite data. The studied area was the Maisky district, which is located in the southeastern part of the Pavlodar region of Kazakhstan. The variants of the research were agricultural lands using sprinkler irrigation and flood irrigation, as well as sites without irrigation. To analyse the relationships, we used the normalized difference vegetation index (NDVI), salinity indices (SI) and soil indices such as SI 1, SI 2, SI 3, SI 4, normalized difference salinity index (NDSI), soil adjusted vegetation index (SAVI), and brightness index (BI). The normalized difference salinity index $(R-NIR)/(R + NIR)$, using a quadratic statistical relationship, showed the best correlation with the laboratory data. The vegetation index NDVI showed the weakest correlation due to dryness or poor crop growth. As a result of the lack of clear control over irrigation and agro-technical measures, the indicators of cation exchange capacity in irrigated plots using the flooding method were higher than in other irrigation methods. During irrigation, it is necessary to ensure clear rules, according to which the supplied water and fertilizers will have a positive effect on the soil and the entire agroecosystem. The methods used in this research can be useful in mapping and studying saline soils using satellite data in natural and climatic conditions of arid and semi-arid regions.

Keywords: arid regions; soil properties; salinity; irrigation; landsat image; remote sensing; vegetation

Saline soils are a group of soils of different genesis and properties that have such a level of soluble salts in their profile that degrades soil fertility and negatively affects the growth and development of most plants (Lopatovskaya & Sugachenko 2010; Hateffard et al. 2022). Plants are the first in the food production chain to be affected by salinity stress, as this inhibits

their basic physiological and biochemical processes such as water absorption and photosynthesis, resulting in overall reduced growth (Munns 2005; Munns & Tester 2008; Rahnema et al. 2010).

Accelerated land degradation now affects more than 30% of the Earth's surface and is a global problem. It occurs mainly in arid regions, as well as in arid

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and desert steppe zones. (Bini 2009). This implies a deterioration in soil quality with a concomitant reduction in ecosystem functions and services (Lal 2015; Šarapatka & Bednář 2015). If the current salinization trend continues, then by 2050 we will see an increase of about 50% in the salinity of cultivated land. The loss of agricultural land is the main reason for the increase in the proportion of the population suffering from a lack of food (Kovda 2008).

Of the present total area of Kazakhstan, which is 272 million hectares, 180 million hectares (60% of the country's territory) are threatened by degradation (Orlova & Saparov 2009; Baiseitova et al. 2018). Degradation takes the form of water and wind erosion, salinization, waterlogging, soil compaction, depletion and desertification processes, which often synergistically accelerate the resulting soil degradation (Shokparova & Issanova 2013). The northern parts of Kazakhstan, which are important crop-growing areas, are mainly sown with spring crops relying on atmospheric precipitation and often suffer from drought (Karatajev et al. 2022). Therefore, the use of an irrigation system is one method of increasing crop yield. However, the improper use of irrigation and the adverse effect of irrigation water quality can affect soil properties due to the accumulation of sodium ions, making soil aggregates unstable. Their destruction is accompanied by the dispersion of clay particles, which leads to the clogging of soil pores (Dhok et al. 2011).

The detection of soil salinity requires analysis of soil samples in water extracts. This is mainly pH values, salt content measured as electrical conductivity (EC), exchangeable sodium and cation exchange capacity (CEC), from which the percentage of exchangeable sodium (ESP) and the ratio of the concentration of sodium (Na^+) to other cations (K^+ , Ca^{2+} and Mg^{2+}) are calculated, also known as sodium absorption ratio (SAR) (Brown et al. 1954; Kertesz & Toth 1994). A significant number of soil samples are required to create a salinity map based on the results of the above salinity measurements. This makes mapping difficult and expensive. Recently, special soil survey methods such as remote sensing have been considered (Fernandez-Buces et al. 2006). Using these methods, it is possible to obtain more results with less labour and more economically compared with traditional methods (Otarov et al. 2018). The development of remote sensing methods for the study of soils and, in our case, for monitoring soil salinity, will allow information to be obtained for management

decisions, such as the implementation of reclamation measures, reconstruction of irrigation systems, crop diversification, selection of methods for sustainable management, etc. (Smanov et al. 2023).

In research by Laiskhanov et al. (2016), the salinization dynamics of irrigated land were studied in southern Kazakhstan using LANDSAT images, and with the normalized difference salinity index (NDSI), it was possible to construct maps of salinity and soil salinity dynamics at a semi-quantitative level. In another study (Suleimanov et al. 2021), the use of GIS demonstrated good mapping capabilities for saline soils. Quadratic statistical dependence, using the method of least squares, enabled the best correlation to be obtained between soil salinity and calculated values of spectral indices for mapping saline soils, which made it possible to quickly identify areas and create salinity maps not only for the study but for the entire territory of the Trans-Ural steppe zone.

The research focuses on the salinization of agricultural soils in the model area of the Pavlodar region, specifically in the Maisky district. The aim of the study was to describe the relationships between the results of laboratory soil analysis and the main spectral indices of salinity and vegetation obtained from Landsat satellite data, which will be useful for the evaluation of larger areas in terms of their agricultural use. In order to achieve the set main aim, goals were set in the analysis of selected soil properties relating to salinization during management with or without irrigation. Another goal was to identify remote sensing spectral indices at selected locations that will reflect the intensity of salinization under different management and will be usable in larger areas.

MATERIAL AND METHODS

The following phases were established for the research work: classification of the area of interest according to the type of land use to identify salinity, laboratory analysis of soils to characterize salinity, regression analysis of data, and mapping of soil salinity using remote sensing.

Study area. Maisky District (Figure 1) was selected for this study, which in the Pavlodar region has a lack of moisture during the period of intense plant growth, and often faces droughts in the region. Its geographic location ranges between 51°0'0"N and 77°30'0"E and covers an area of 18 100 km². The study area is located in the dry zone of the Pavlodar region. The climate

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of the region is distinctly continental. The average temperature in January is from -15°C to -17°C , in July from $+20^{\circ}\text{C}$ to $+22^{\circ}\text{C}$. The annual amount of precipitation is 200–250 mm (Almishev & Bondarenko 2006). According to the classification of soil types of the FAO-UNESCO soil map of the world, the study area on all three farms belongs to the Haplic Kastanozems class (IUSS Working Group WRB 2022), only the extreme southeastern part is in the desert-steppe (semi-desert) zone on light chestnut soils. The largest surface water source is the Irtysh River, which is the main source of irrigation for increasing crop productivity.

Sites with different types of irrigation, i.e., sprinkler method, flood method and farmland without irrigation, were selected for the research (Figure 1). The natural conditions of the selected farms enable the cultivation of cereals such as wheat, barley, oats, millet, buckwheat, and corn, as well as legumes, oilseeds and vegetables. The harvest of cereals in these areas is usually in the first half of August, if there is sufficient moisture during the establishment of the crop (Baisholanov 2017).

Research structure. This research proposed an integrated approach focusing on salinity, vegetation indices, and field data to develop a multiple regression

equation for predicting soil salinity from satellite image analysis. The development diagram of the methodology is in Figure 2.

Soil sampling. Soil sampling was carried out in early September, when the highest level of salt accumulation was observed in the topsoil. For chemical analysis, average samples consisted of ten-point samples taken from one sampling area at 0–20 cm depth. Samples were collected in areas of 2 ha from different land use: including non-irrigated, irrigated, flood irrigation.

Soil samples were taken with a soil sampler. In total, an average of 30 soil samples were taken from 3 farms where grain crops were grown. Thus, 10 samples were taken from individual types of water management farms. The most adequate soil salinity and the effect of salts on plant growth reflect the results of soil solution analysis (GOST 17.4.4.02 2018).

Soil properties analysis. The water extraction method allows the determination of composition and salinity, assessment of chemical composition and degree of soil salinity (Shokparova & Isanova 2013; Molchanova 2019).

The chemical composition of the aqueous extract was determined by extracting soluble salts from

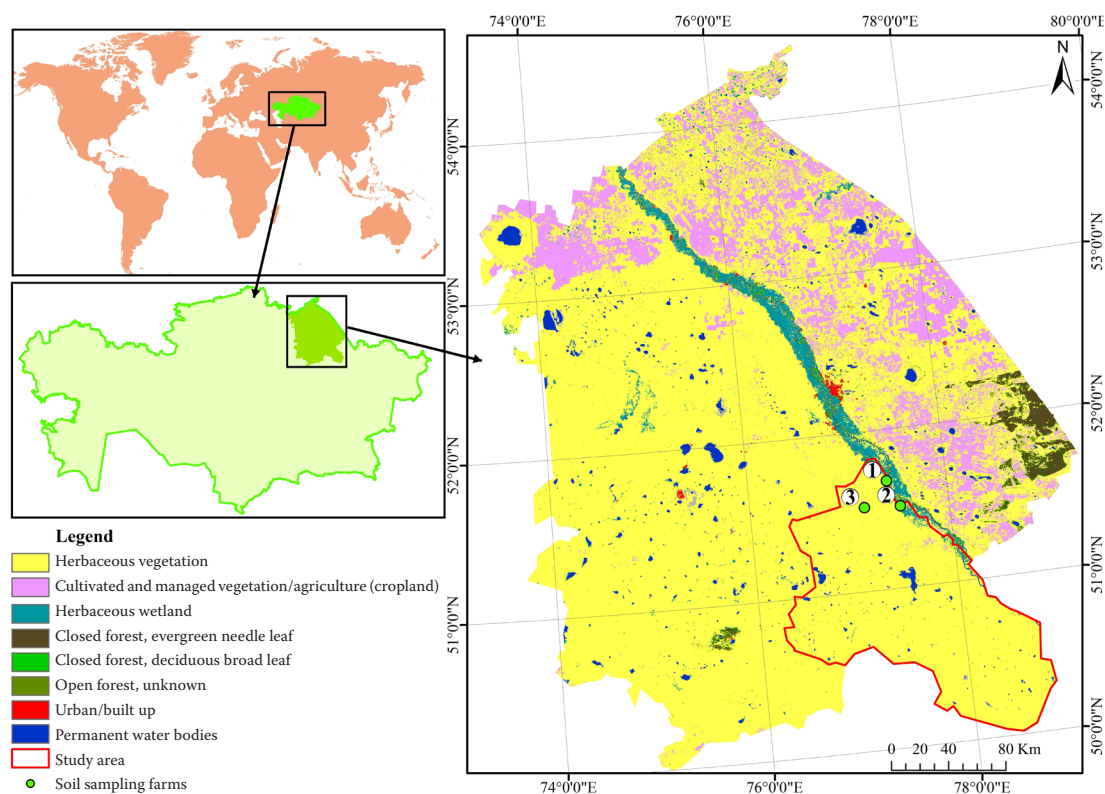


Figure 1. Study area of Maisky district in Pavlodar region

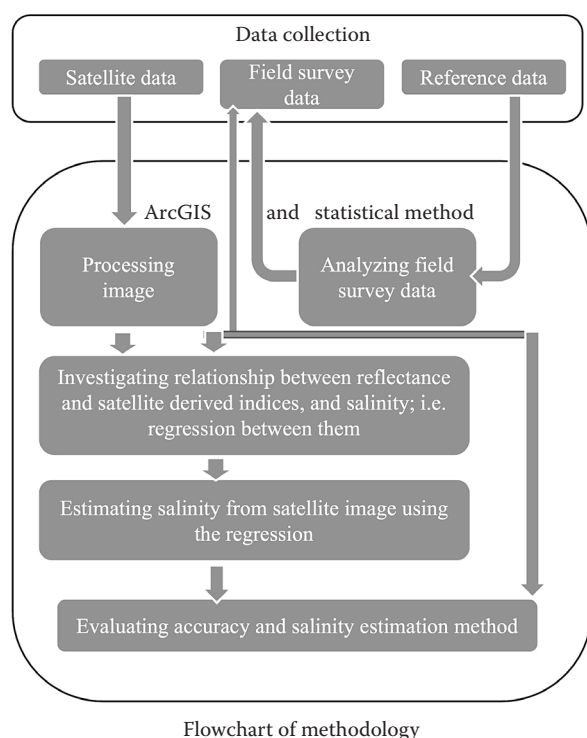


Figure 2. Proposed integrated approach for soil salinity detection

the soil with water at a ratio of soil to water 1 : 5 by state standards (GOST 26423-85 2011) with subsequent definition in investigated extracts of ions of Ca^{2+} , Na^{+} , Mg^{2+} , K^{+} and EC, total dissolved solids (TDS), pH.

EC, TDS, and pH were determined by means of XS Revio multiparameter; Ca^{2+} , Na^{+} , Mg^{2+} , K^{+} were determined by AAS Avanta.

In order to indicate sodium soils, we used the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) cation exchange capacity (Seilsepour et al. 2009).

$$\text{SAR} = \text{Na}^{+} / \sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+}) / 2} \quad (1)$$

where:

SAR – sodium adsorption ratio;
 Na^{+} , Ca^{2+} , Mg^{2+} – measured exchangeable Na^{+} , Ca^{2+} and Mg^{2+} , respectively (meq/100 g).

$$\text{ESP} = (\text{Na}^{+} / \text{CEC}) \times 100 \quad (2)$$

where:

ESP – exchangeable sodium percentage (%);
 CEC – cation exchange capacity (meq/100 g).

Statistical evaluation. We used MS Excel software to calculate statistical variables such as mean, coefficient of variation, and coefficient of determination. Pearson's correlation was used to assess the statistical significance of differences. Pearson's correlation is a method of covariance that is considered an appropriate method for measuring the relationship between two continuous variables (Singh & Jain 2021). To find dependencies between indicators, we used correlation and determination coefficients; the coefficient of variation showed the variability of the studied values and properties.

Remote sensing data and software. The research used images taken by Landsat 8 clear-sky satellites from WRS-2 path151, row 024, processing level 1T, from the United States Geological Survey portal (earthexplorer.usgs.gov) for the months of July and October 2021. A total of 30 points were taken as test samples to verify the accuracy with remote sensing data.

Subsequently, spatial analysis tools in ArcMap (Ver. 10.3) software were used to calculate and analyse the indices, which are described in Table 1. Excel software was used to normalize the indices. Soil salinity is estimated using EC, TDS, and soil cations as measured in the laboratory. Based on the results,

Table 1. Calculated spectral indices for soil salinity mapping

Acronym	Spectral indices	Equations	Sources
SI 1	salinity index 1	$\text{SI 1} = \sqrt{\text{green}^2 + \text{red}^2}$	Douaoui et al. (2006)
SI 2	salinity index 2	$\text{SI 2} = \sqrt{\text{green} \times \text{red}}$	Douaoui et al. (2006)
SI 3	salinity index 3	$\text{SI 3} = \sqrt{\text{blue} \times \text{red}}$	Khan et al. (2001)
SI 4	salinity index 4	$\text{SI 4} = (\text{red} \times \text{NIR}) / \text{green}$	Abbas and Khan (2007)
NDVI	normalized difference vegetation index	$\text{NDVI} = (\text{NIR} - \text{red}) / (\text{red} + \text{NIR})$	Khan et al. (2001)
NDSI	normalized difference salinity index	$\text{NDSI} = (\text{red} - \text{NIR}) / (\text{red} + \text{NIR})$	Khan et al. (2005)
SAVI	soil adjusted vegetation index	$\text{SAVI} = (1 + L) \times \text{NIR} - \text{red} / L + \text{NIR} + \text{red}$	Bouaziz et al. (2011)
BI	brightness index	$\text{BI} = \sqrt{\text{nir}^2 + \text{red}^2}$	Khan et al. (2005)

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analysis was performed to determine the relationship between reflectance values and soil salinity indices for soil salinity estimation from Landsat 8 imagery (Nguyen et al. 2020).

Index selection. Monitoring soil salinity information using a feature space constructed by different spectral indices in remote sensing images is a current research frontier method of remote sensing soil salinity monitoring. At present, vegetation index, salinity index, brightness index, etc. are commonly used. Various spectral indices include many forms, e.g.: vegetation index includes normalized vegetation index, normalized difference salinity index, etc.; the salt index (SI) includes the normalized salt index, SI 1, SI 2, SI 3, SI 4, etc. (Table 1).

RESULTS AND DISCUSSION

The quantitative results of the main parameters of soil salinity for different forms of management with descriptive statistics such as maximum value (MAX), minimum value (MIN), standard deviation (SD), and mean value are shown in Table 2 and 3.

The variable EC is used to monitor soil salinity due to the practicality of measurement and high correlation with total dissolved solids, as it represents the phenomenon of transfer of electric cur-

rent developed by charged particles, ionic solutes (cations and anions) and colloids to the force acting on the electric field (Campos Carmona et al. 2010). As a result, soil samples from all agricultural plots had an electrical conductivity below 0.06 dS/m. According to the classification presented by Solangi et al. (2019), or Kotuby-Amacher et al. (2000), it appears that all studied soil areas belong to non-saline soils. In the analysed region, lighter soils predominate, e.g. sandy loams, loams and sands (Baisholanov 2017), from which ions concentrated in deeper horizons are more easily washed out.

SAR and ESP indicators were also analysed. According to the proposed classification of the Natural Resources Conservation Service (NRCS), the soil samples studied by us belong to non-saline soils in terms of SAR and ESP.

This study is in agreement with authors who showed that vegetation soil salinity index and normalized difference vegetation index have a low correlation with field data due to insufficient canopy density (Suleymanov et al. 2021).

Several studies have found a positive correlation between NDSI and laboratory data. In studies (Avila Aceves et al. 2019; Laiskhanov et al. 2016), NDSI provided greater accuracy in the study area, so the obtained values were correlated with soil electrical

Table 2. Maximum (MAX), minimum (MIN), average and standard deviation (SD) values of pH, electrical conductivity (EC), total dissolved solids (TDS), percentage of exchangeable sodium (ESP), sodium absorption ratio (SAR), and soluble cations

	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CEC	ESP	EC (dS/m)	TDS (mg/l)	pH	SAR
	(meq/100 g)									
Sprinkler/spray irrigation land										
MAX	6.16	2.27	0.33	1.33	10.09	3.57	0.06	45.30	6.87	0.16
MIN	4.84	1.65	0.23	0.95	7.96	2.44	0.05	33.60	6.65	0.11
SD	0.62	0.28	0.04	0.15	0.90	0.42	0.01	4.40	0.09	0.02
Average	5.45	1.94	0.28	1.19	8.87	3.16	0.06	39.42	6.76	0.15
Flood irrigation land										
MAX	22.81	7.39	1.60	1.03	32.57	5.25	0.06	46.70	7.22	0.43
MIN	20.93	6.16	0.66	0.85	29.17	2.26	0.05	33.90	6.79	0.18
SD	0.89	0.46	0.44	0.07	1.38	1.34	0.01	6.34	0.17	0.11
Average	21.89	6.64	1.14	0.92	30.60	3.69	0.06	39.74	6.93	0.30
Land without irrigation										
MAX	10.18	2.91	0.24	1.27	14.55	2.10	0.05	37.60	6.83	0.10
MIN	6.21	1.96	0.16	0.89	9.43	1.46	0.04	28.60	6.50	0.07
SD	1.44	0.33	0.02	0.14	1.72	0.20	0.01	3.06	0.09	0.01
Average	7.88	2.40	0.20	1.10	11.57	1.75	0.05	33.04	6.67	0.09

Table 3. Maximum (MAX), minimum (MIN), average and standard deviation (SD) of indexes values

	NDSI	SI 1	SI 2	SI 3	SI 4	NDVI	SAVI	BI
Sprinkler/spray irrigation land								
MAX	0.09	0.24	0.17	0.16	0.23	0.54	0.13	0.28
MIN	0.08	0.22	0.16	0.15	0.21	0.47	0.12	0.25
SD	0.003	0.004	0.003	0.002	0.007	0.021	0.005	0.006
Average	0.08	0.23	0.16	0.16	0.22	0.51	0.12	0.27
Flood irrigation land								
MAX	0.15	0.24	0.17	0.16	0.26	0.42	0.23	0.29
MIN	0.10	0.20	0.14	0.14	0.20	0.25	0.16	0.23
SD	0.017	0.014	0.010	0.009	0.024	0.071	0.026	0.022
Average	0.13	0.23	0.16	0.15	0.24	0.35	0.19	0.27
Land without irrigation								
MAX	0.09	0.26	0.18	0.17	0.27	0.30	0.14	0.30
MIN	0.07	0.23	0.16	0.16	0.19	0.18	0.11	0.23
SD	0.007	0.009	0.006	0.005	0.027	0.043	0.010	0.023
Average	0.08	0.24	0.17	0.16	0.22	0.23	0.12	0.27

NDSI – normalized difference salinity index; SI – salinity index; NDVI – normalized difference vegetation index; SAVI – soil adjusted vegetation index; BI – brightness index

conductivity and Cl^- , Na^+ and Ca^{2+} concentrations, as well as Mg^{2+} ions determined in the laboratory. Our results confirm the correlation and the normalized difference salinity index showed the highest correlation between the results of cations, SAR, ESP (Figure 3 and 4).

It is also known that the cation exchange properties of soil are almost completely determined by clay

and organic colloidal fractions (Nešić et al. 2015). In general, sandy soils show less salinity because larger particles do not bind and easily percolate through the soil. Conversely, binding occurs to clay particles and these soils remain more saline (Tang et al. 2020; IAARD 2008).

The calculated CEC as the sum of exchangeable cations was performed according to the formu-

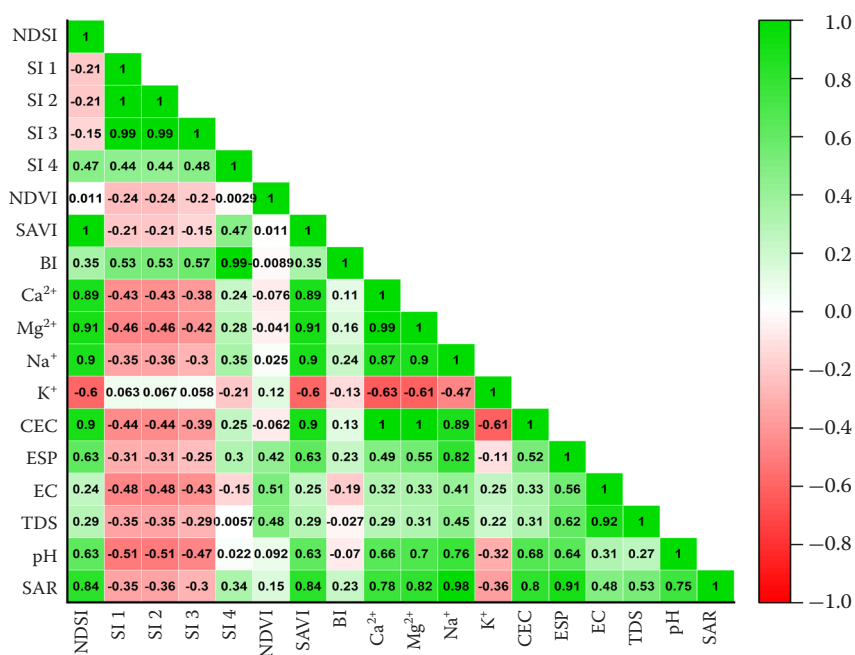


Figure 3. Correlation matrix
NDSI – normalized difference salinity index; SI – salinity index; NDVI – normalized difference vegetation index; SAVI – soil adjusted vegetation index; BI – brightness index; CEC – cation exchange capacity; EC – electrical conductivity; TDS – total dissolved solids; ESP – percentage of exchangeable sodium; SAR – sodium absorption ratio

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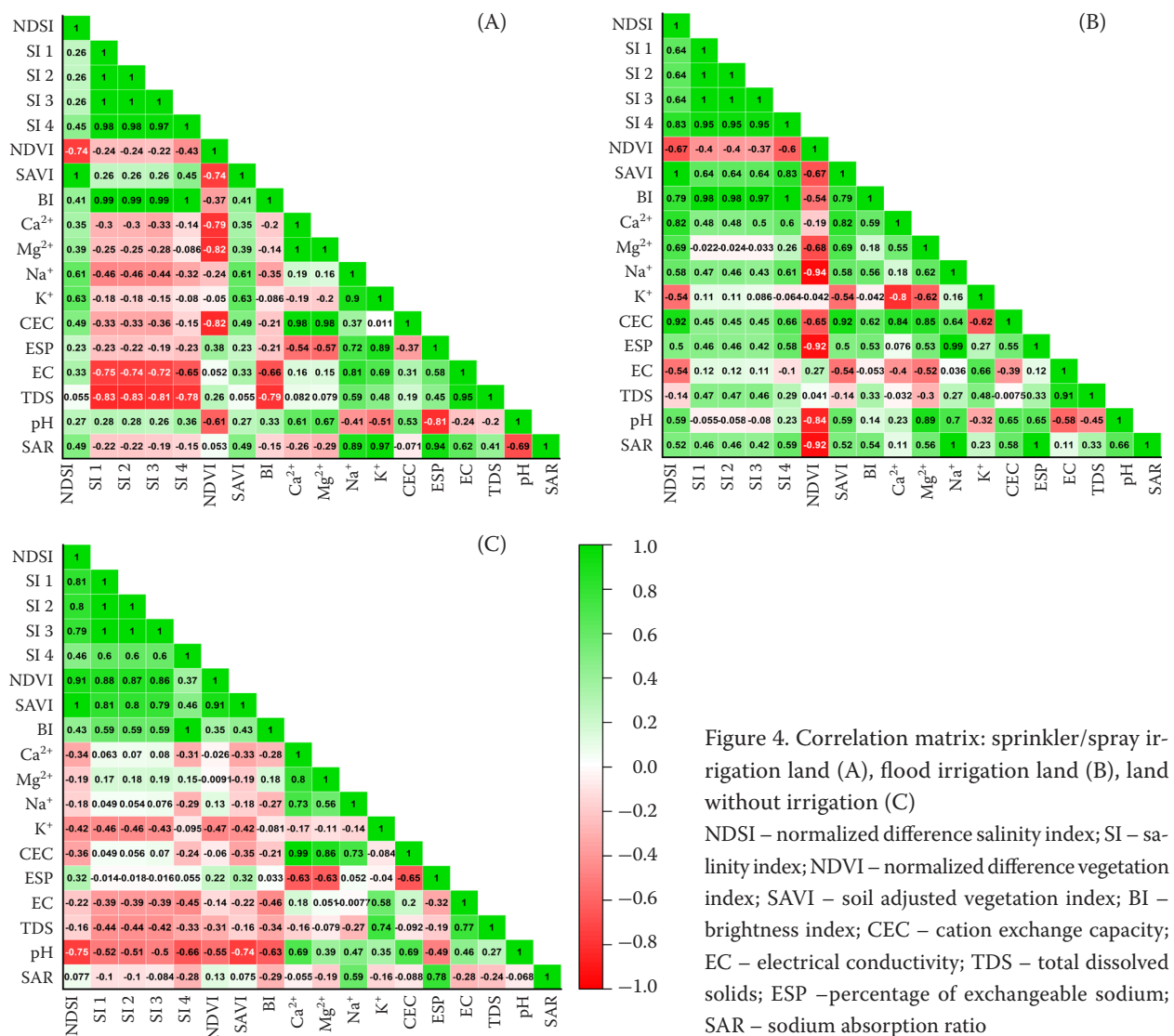


Figure 4. Correlation matrix: sprinkler/spray irrigation land (A), flood irrigation land (B), land without irrigation (C)

NDSI – normalized difference salinity index; SI – salinity index; NDVI – normalized difference vegetation index; SAVI – soil adjusted vegetation index; BI – brightness index; CEC – cation exchange capacity; EC – electrical conductivity; TDS – total dissolved solids; ESP – percentage of exchangeable sodium; SAR – sodium absorption ratio

la published by Shafie et al. (2012) and is shown as Equation (3)

$$\text{CEC} = \sum \text{exchangeable cations (meq)/100 g soil (3)}$$

The study found a strong correlation between NDSI and measured CEC, as shown in Figure 5.

Obtaining information on cation exchange capacity is becoming increasingly important on dry land as this suffers from many problems such as lack of sufficient water to support plant growth and land degradation (Adam et al. 2021). Spatio-temporal mapping of soil salinization results showed that agricultural land of Maisky District, closer to the Irtysh River, using flood irrigation, has increased CEC content. The results of cation exchange capacity of soil samples from this area range from 29.17 to 32.57 meq/100 g with a standard deviation

of 1.38 (Table 2), (Figure 6). The operation of flood irrigation in this region is reduced to a one-off flooding of the soil in early spring and coincides with natural flooding. (Committee for Land Management 2021).

Irrigation applied by the flooding method creates zones of salinity in the soil depending on the frequency and amount of water applied in each irrigation cycle. At the end of each irrigation cycle, the soil dries out and salts are concentrated, resulting in a negative effect on plant growth (Zaman et al. 2018). Water management is a major limiting factor in the productivity of saline soils, occurring under extreme conditions of excess water or drought (Toth et al. 1991). In studies by Liu et al. (2022), the soils of the area of the southern part of the Shardara reservoir and the left bank of the irrigated area of the Syrdarya River, mainly soils

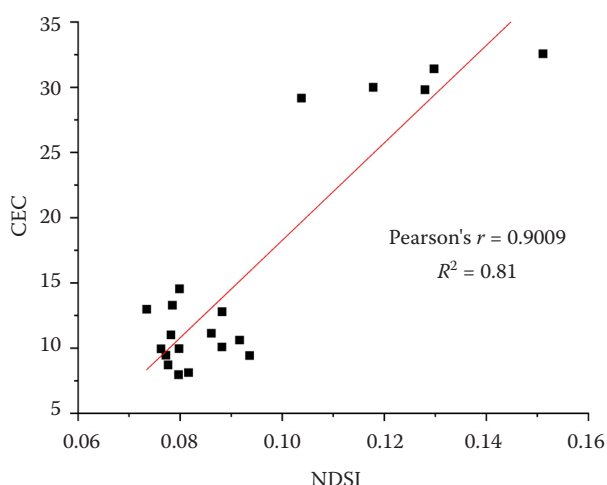


Figure 5. The relationship between cation exchange capacity and NDSI

CEC – cation exchange capacity; NDSI – normalized difference salinity index

of the loam category, were subjected to salinization to varying degrees.

Soil CEC higher than 15 meq/100 g according to the classification given in Table 4, indicates a higher clay content, poor internal drainage and an influence on the soil structure (Lambooy 1984). A low CEC of 1 to 5 meq/100, on the other hand, indicates sandy soils prone to drying out, which require an increased supply of organic matter.

The dark chestnut soils of the Maisky district, in the vast majority of light mechanical composition, are predominantly light loamy and sandy, and sandy in the southern region. This is a consequence of their formation on the ancient alluvial deposits of the Irtysh, which have a light mechanical composition (Dzhanpeisov et al. 1960; Durasov & Tazabekov 1981). In the analysis of remote sensing data (Tabyldinov & Galymzhan 2019), accompanied by the study of stock material, it was possible to create a map of the current state of the soil cover of the Akkulinsky district, which borders our study area in the west across the Irtysh River. Also, this paper describes how the surveyed area is the result of ancient alluvial and lacustrine-alluvial deposits, and chestnut, dark chestnut soils of this area in terms of mechanical composition from sandy to heavy loam.

Soil structure plays an important role in the salinization of irrigated agricultural land. As leaching will remove more dissolved salts from the root zone, sandy soils can tolerate higher salt content in irrigation water. Conversely, soils with a higher clay

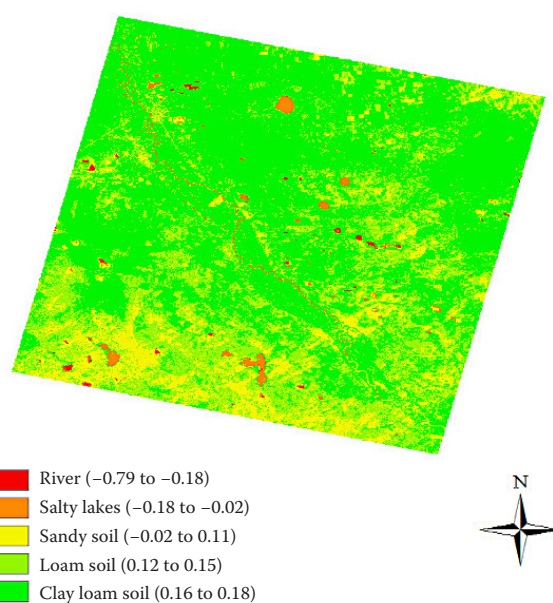


Figure 6. Map of the cation exchange capacity (in meq/100 g) based on the normalized difference salinity index

content are more at risk than sandy soils because excess sodium binds to them and can cause soil dispersion. To map the saline soils of the steppe zone of the Maisky district, it is most expedient to use the normalized difference salinity index. This allows rapid identification, and creation of salinity maps not only of the study area, but of the entire territory of the Pavlodar steppe zone.

Our research also states that, during springtime, on agricultural lands where flooding is used, an excessive amount of water raises the groundwater level. Then, in the summertime, the upward movement of soil moisture significantly prevails over the downward movement. In this regard, the action of these factors causes the ascending currents of water to pull the cations that have passed into a highly mobile state to the upper soil horizons.

Table 4. Cation exchange capacity (CEC) at pH 7.0 of different soil textures (Mengel 2012; Sonon et al. 2017)

Soil components and texture	CEC (meq/100 g)
Sand	1–5
Fine sandy loam	5–10
Loam	5–15
Clay loam	15–30
Clay	> 30

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CONCLUSION

The lack of information on salt loading of soils and irrigation water in many agricultural regions of the world, often associated with inappropriate management, leads to a number of negative consequences for the soil and the entire agroecosystem, for both production and non-production functions. This is a problem of salinization in Kazakhstan as well, and therefore, it is necessary to work on a monitoring proposal that will help not only from a scientific point of view but can provide important information for the management sphere and for farmers.

Modern technologies, such as geographic information systems, can significantly help in this, because by using innovative methods, compared to traditional methods, results can be achieved over larger areas, and usually at lower cost.

The Landsat satellite data we used showed the potential for mapping degraded soils according to salinity. Quadratic statistical dependence using the method of least squares resulted in the best correlation between soil salinity and calculated values of spectral indicators. For the mapping of saline soils in the steppe zone of the Pavlodar region, the normalized difference salinity index proved to be the most appropriate method. In subsequent investigation, we intend to focus, using the information from this research, on the study of water-soluble salts in individual soil horizons, on a wider scale of the affected steppe areas of the Pavlodar region.

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