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Comprehensive Analysis of Soil Salinization Dynamics in Semi-Arid Regions of Uzbekistan Using GIS and Remote Sensing Indices

This study presents a comprehensive analysis of soil salinization processes in the Kattakurgan district (Uzbekistan) using Geographic Information Systems (GIS) and remote sensing (RS) indices. The research integrates natural components, including geomorphology, hydrogeology, annual precipitation, slope gradient, aspect, and soil types, with key remote sensing indicators such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Tasseled Cap Wetness (TCW), Bare Soil Index (BSI), Salinity Index (SI), and Normalized Difference Salinity Index (NDSI). Landsat 8/9 satellite imagery was employed to perform spatial analysis within a GIS environment. The results revealed high salinization in the central and western parts of the district, while irrigated areas exhibited moderate soil moisture and vegetation cover. TCW and NDMI indices effectively reflected soil moisture and vegetation density, whereas SI and NDSI accurately delineated the spatial distribution of salinization processes. These findings are closely linked to hydrogeological conditions, topography, and vegetation, enabling the identification of high-risk salinization zones in semi-arid regions. Furthermore, GIS and RS-based analyses provide essential information for assessing ecological stability, planning irrigation and reclamation measures, and optimizing water resource management. The integrated approach allows precise identification of primary salinization zones, evaluation of vegetation and water-related ecological processes, and supports informed agro-technical and land reclamation decisions. This study demonstrates that the combination of GIS and RS indices is a reliable and effective tool for monitoring soil salinization and guiding sustainable land management in semi-arid areas.

Keywords: Soil salinization, GIS, remote sensing, NDVI, NDMI, TCW, BSI, SI, NDSI, semi-arid region, Kattakurgan district.

Introduction

As the global population continues to expand, food scarcity is increasingly emerging as a pressing global challenge. This issue is driven by multiple interrelated factors, including the limited capacity for agricultural production, growing pressure on freshwater resources, constraints on cultivable land availability, and ongoing climate change manifested through rising temperatures and increasing aridity. Among these drivers, soil salinization has intensified worldwide and has become one of the most critical constraints to sustainable agricultural development and environmental resilience. Soil salinization not only deteriorates soil structure and fertility but also substantially impairs crop growth and productivity, thereby posing significant risks to food security and regional economic stability [1–3].

According to the definitions proposed in studies by Portuguese soil scientists, soil salinization refers to the accumulation of soluble salts within the soil profile. This process is commonly associated with high evaporative demand and may be further exacerbated by seawater intrusion and other geogenic or anthropogenic factors. As emphasized by Ayers and Westcot, elevated salt concentrations increase osmotic stress in the soil matrix, which in turn reduces soil water availability and restricts water uptake by plant roots. Once salinity levels exceed crop-specific tolerance thresholds, soil salinization adversely affects plant growth, transpiration, and yield formation, ultimately resulting in crop failure [4-5].

A substantial body of literature identifies soil salinization as a major driver of land degradation and agricultural yield decline [6-7]. In arid and semi-arid regions, agricultural production is predominantly dependent on irrigated farming systems. Under these conditions, high evapotranspiration rates, low precipitation, and soil physical properties that limit infiltration facilitate the upward movement and accumulation of salts in the topsoil. This process alters soil physicochemical characteristics and constrains key soil functions, making salinization particularly severe in dryland environments.

From a process-oriented perspective, soil salinization is commonly classified into two principal types: primary (natural) salinization and secondary (anthropogenic) salinization. Secondary salinization is mainly induced by prolonged drought, the application of saline or low-quality irrigation water, and excessive use of chemical fertilizers. These impacts are significantly intensified in areas characterized by insufficient or poorly managed drainage infrastructure [8-9].

Primary salinization, in contrast, is driven by natural factors such as parent material composition, physicochemical weathering of minerals, and marine water intrusion processes. Irrigated agricultural lands are among the most vulnerable socio-ecological systems, with soil salinization contributing to the global loss of approximately 14 km^2 of fertile land on a daily basis [10-11].

To mitigate and manage soil salinization effectively, numerous studies emphasize the importance of producing reliable salinity maps. Continuous monitoring of salinity dynamics, combined with an integrated assessment of geological structure, hydrogeological conditions, topography, slope gradient, slope aspect, and climatic variables, enables a more comprehensive understanding of the mechanisms underlying salinization processes and supports the development of targeted and context-specific management strategies [1, 3, 5, 11].

Conventional approaches to salinity assessment are labor-intensive, time-consuming, and spatially constrained, as they rely primarily on point-based field measurements conducted over short temporal intervals [1, 3, 10–16]. Consequently, the integration of advanced technologies is essential to enhance the efficiency and reliability of decision-making processes in soil salinity management.

A growing body of evidence demonstrates that Remote Sensing (RS) and Geographic Information System (GIS) techniques, particularly those based on satellite imagery, offer high potential for detecting, monitoring, and mapping soil salinization [12, 14]. Remotely sensed data facilitate the analysis of spatial and temporal variability, provide regional—to continental-scale coverage, and enable cost-effective long-term monitoring.

In recent years, remote sensing has become a cornerstone of soil salinity assessment due to its ability to provide high-resolution, multi-temporal observations across extensive geographic areas [10–12, 14, 16-17].

Materials and methods

To investigate soil salinization using remote sensing techniques, Kattakurgan District of Samarkand Region was selected as the study area. Geographically, the district is located in a foothill and intermontane zone, characterized by complex natural conditions.

From a geological perspective, the northern part of the study area is composed predominantly of Ordovician, Devonian, and Carboniferous metamorphic and magmatic rocks of the Paleozoic era. In contrast, the central part of the territory coincides with the axis of the Zarafshan syncline, where Quaternary deposits are widely distributed along the river valley. The hydrogeological conditions of the region closely correspond to its geological structure. In areas dominated by Paleozoic formations, groundwater mineralization reaches up to 1 g/L, while the degree of groundwater mineralization increases progressively toward the river channel (Fig. 1).

The climate of Kattakurgan District is sharply continental, characterized by hot, dry summers and cold, dry winters. The average annual precipitation is approximately 289 mm (Fig. 2) [18-19]. According to comprehensive soil surveys conducted in the region, the dominant soil types include gray soils (serozems) and mountain brown soils (Fig. 3).

To identify the key factors influencing soil salinization in the study area, multiple data sources were utilized:

- Remote sensing data: Landsat and Sentinel-2 satellite imagery were employed to derive spectral indices indicative of soil and vegetation conditions.
- Topographic data: Digital Elevation Models (DEMs) were used to extract elevation, slope gradient, and slope aspect parameters.
- Climatic data: Annual precipitation and evapotranspiration data were obtained from meteorological sources.
- Anthropogenic factors: Distance to roads and proximity to rivers were derived from OpenStreetMap datasets to assess human activity and water availability.
- Soil-related factors: Soil moisture and other relevant soil properties were determined through field investigations.

Result and Discussion

Kattakurgan District is located in the middle reaches of the Zarafshan River, where the landscape is dominated by erosional–accumulative terraces. These geomorphological conditions have facilitated the deposition of gravel layers at depths of approximately 1-2 m within the soil profile, thereby promoting the development of natural drainage conditions in the area.

An analysis of groundwater mineralization, flow direction, and depth to the aquifer revealed several key patterns. Due to the gradual increase in elevation toward the northern and southern parts of the district, groundwater flow is predominantly directed toward the Zarafshan depression. In addition, since the Zarafshan River flows westward, groundwater movement also exhibits a westward component toward the Lower Zarafshan region. Correspondingly, the groundwater table gradually decreases from east to west, reflecting the regional topographic gradient and hydrodynamic regime.

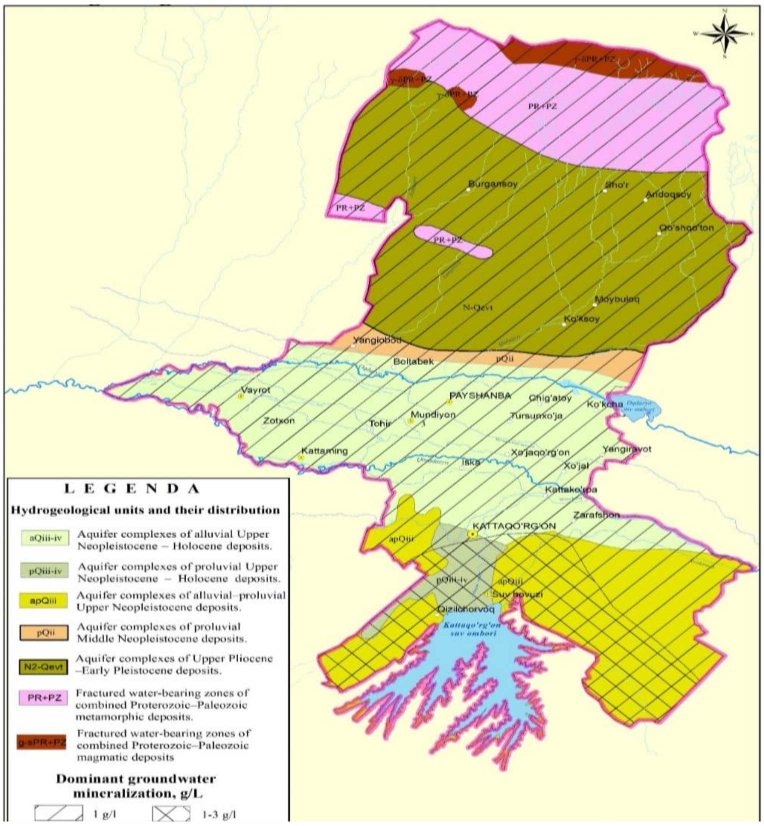

Figure 1. Hydrogeological characteristics of Kattakurgan District (authors' compilation)

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The observed spatial variability of groundwater mineralization in the study area is strongly controlled by geological and geomorphological conditions, which play a critical role in soil salinization processes. In both confined and unconfined aquifers, groundwater mineralization generally remains around 1 g/L, reflecting the influence of Paleozoic lithological units and relatively effective natural drainage conditions. However, a distinct increase in mineralization levels (1–3 g/L) is evident in the vicinity of the Kattakurgan Reservoir, where hydrogeological conditions favor groundwater accumulation.

This pattern can be primarily attributed to the structural influence of the Kattakurgan syncline, which acts as a natural groundwater convergence zone. The prolonged residence time of groundwater within this synclinal structure enhances water–rock interactions, leading to increased dissolution of soluble salts and subsequent enrichment of groundwater mineral content. When combined with high evapotranspiration rates characteristic of the region, this process significantly increases the upward movement of saline groundwater through capillary rise, thereby promoting secondary soil salinization in overlying soils.

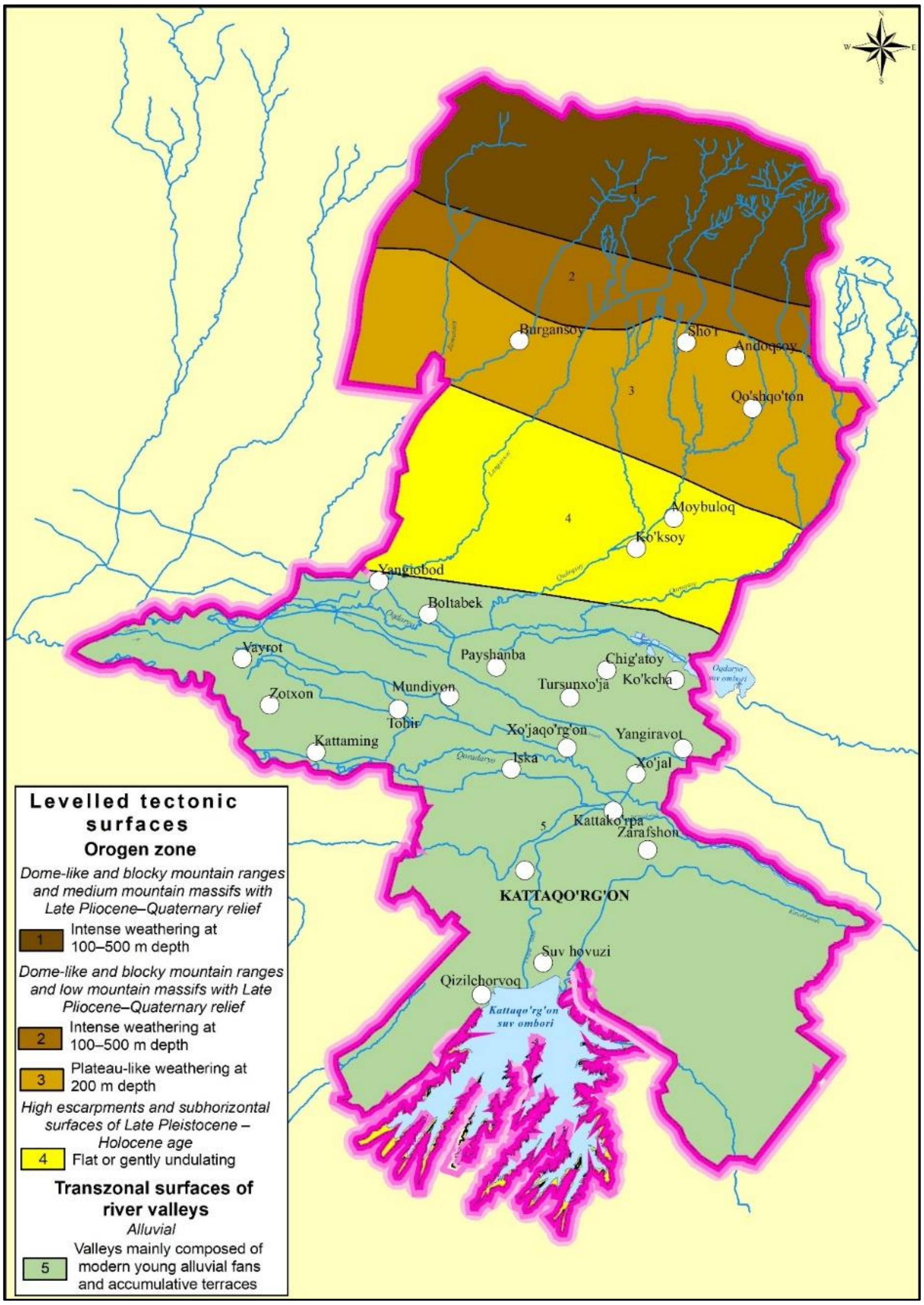

Figure 2. Geomorphological setting of the study area (authors' compilation)

The geomorphological heterogeneity of Kattakurgan District further intensifies salinization dynamics. The presence of three distinct geomorphological units—namely, the orogenic (mountain) zone, foothill proluvial–deluvial plains, and alluvial river valleys—creates pronounced spatial differences in surface and subsurface hydrological behavior (Fig. 2). In particular, the foothill plains and alluvial valleys, characterized by gentle slopes and fine-textured sediments, function as accumulation zones for salts transported from higher elevations. These areas are therefore more vulnerable to salinization, especially under intensive irrigation practices and insufficient drainage management.

Overall, the interaction between geological structure, groundwater mineralization, and geomorphological setting emerges as a key driver of soil salinization in the study area. These findings underscore the importance of integrating hydrogeological and geomorphological analyses into salinity risk assessments and remote sensing–based monitoring frameworks to support sustainable land and water management strategies in arid and semi-arid environments.

The northern part of the region is distinguished by dome-shaped and blocky mountain ranges belonging to the Late Pliocene–Quaternary age. In this area, relief forms developed on deeply fractured, thick metamorphic and igneous rocks at depths of 100–500 m predominate.

Moving southward, the relief gradually transitions into lower mountains and foothills. The piedmont zone, with elevations up to 200 m, consists of dissected plateaus and proluvial–deluvial cones. This zone is covered by deposits of heterogeneous mechanical composition that are highly susceptible to erosion, have low permeability, and are particularly vulnerable to salinization processes. Salinization is intensified here because groundwater rising from river valleys brings dissolved salts to the surface, where they accumulate due to strong evaporation.

The southern part is occupied by the Zarafshon River valleys and the alluvial plains surrounding the Kattakurgan Reservoir. These areas are composed mainly of young alluvial deposits, accumulative terraces, and sandy–loamy sediments. This zone is characterized by high soil moisture and a relatively shallow groundwater table. As a result, strong capillary rise of water occurs, creating favorable conditions for the intense development of soil salinization processes.

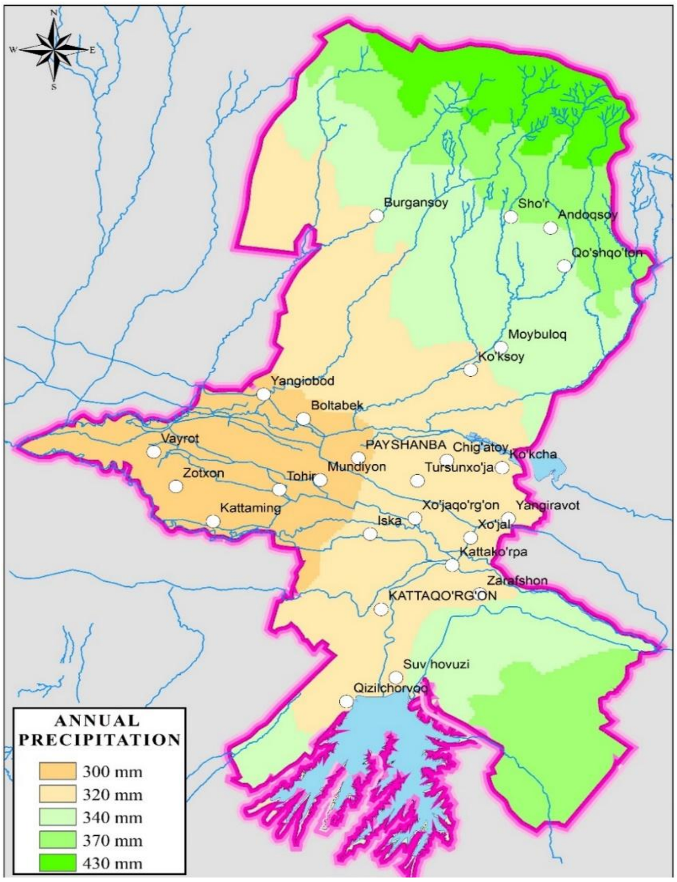

Figure 3. Annual precipitation map of Kattakurgan district (compiled by the authors based on WorldClim data)

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The geomorphological stratification of the study area plays a decisive role in shaping the dynamics of soil moisture, groundwater levels, evapotranspiration intensity, and salinization processes. In particular, the flat topography of alluvial plains, combined with shallow groundwater, facilitates rapid evaporation, which promotes salt accumulation in the soil profile. Conversely, piedmont regions, characterized by lower permeability and more heterogeneous relief, are more susceptible to secondary salinization, highlighting the interplay between terrain morphology and hydrogeochemical processes.

Despite relatively low groundwater mineralization, the region experiences extreme continental climate conditions, characterized by high temperatures and limited precipitation. These factors collectively accelerate evapotranspiration, thereby intensifying surface soil desiccation and promoting salinization. According to the National Atlas of Uzbekistan, the area receives approximately 2,800–3,000 hours of sunshine annually, corresponding to 7,900–8,300 MJ of total solar radiation per square meter, of which 6,000–6,900 MJ is direct radiation. Seasonal variations in atmospheric pressure (1,024–1,003 mb) and moderate wind speeds (1-2 m/s in winter, ~1 m/s in summer) further influence the water balance by modulating both evaporation and convective transport of moisture [20-21].

Climatic data reported by F. Abdikulov indicate a mean annual air temperature of 14.8°C, with extremes reaching 27.4°C in July and dropping to 2.9°C in January. Relative humidity exhibits pronounced seasonal variation, ranging from 43% in summer to 77% in winter [18]. Precipitation patterns are equally heterogeneous: WorldClim datasets estimate average annual rainfall at ~300 mm in the Zarafshan valleys and up to 430 mm in the Aktou Range (Fig. 3), emphasizing the role of topography in modulating local hydrological inputs.

For the assessment of soil salinization using remote sensing and GIS approaches, reference evapotranspiration (ET_o) emerges as a critical parameter, providing a quantitative basis for evaluating the regional water balance and the progression of salinization processes. In this study, ET_o was computed using the FAO-56 Penman–Monteith model, ensuring methodological consistency with internationally recognized standards (1) [22]:

$$ET_O = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \quad (1)$$

Notations:

ET_o – reference evapotranspiration;
Δ – slope of the saturation vapor pressure curve;
Rn – daily net radiation;
γ – psychrometric constant;
T – mean daily air temperature at 2 m height;
U_2 – wind speed at 2 m height;
e_s – saturation vapor pressure;
e_a – actual vapor pressure.

The integration of geomorphological, climatic, and hydrological data thus allows for a nuanced interpretation of salinization dynamics, illustrating how landscape morphology, climate variability, and groundwater characteristics collectively influence soil-water interactions and agroecological vulnerability.

The above (1) formula incorporates key climatic parameters such as solar radiation, air temperature, wind speed, and atmospheric humidity, while also enabling the analysis of evapotranspiration processes influenced by groundwater, hydrogeological conditions, and topography (e.g., slope aspect). Using this approach, the annual reference evapotranspiration (ETo) for the study area was estimated at approximately 1,700–1,760 mm. This exceptionally high potential evapotranspiration serves as a critical indicator for evaluating regional water resource dynamics and soil salinization processes.

Climatic characteristics indicate that evapotranspiration sharply increases during summer months, whereas the near absence of rainfall during this season reduces surface soil moisture to minimal levels. Under such conditions, particularly in river valleys and irrigated areas with relatively shallow groundwater, intensive evapotranspiration and evaporation occur even within the soil aeration zone. The resulting upward movement of soil solutions, followed by water loss through evaporation, leads to salt accumulation in the surface soil layer. Consequently, high ETo values, low precipitation, and shallow groundwater collectively exacerbate salinization in these areas.

Topography, particularly slope aspect, plays a significant role in soil salinization. In Uzbekistan, western, northwestern, and northern slopes receive relatively less solar radiation, retain moisture for longer periods, and tend to have denser vegetation cover. Conversely, southern slopes, characterized by sparse vegetation, experience rapid runoff and rill formation. Direct solar radiation incidence at steep angles and prolonged exposure on southern slopes enhances evaporation from both the soil and shallow groundwater, causing salts to accumulate. Additionally, rainfall on southern slopes often either evaporates before infiltrating or generates surface runoff, preventing effective leaching of salts. In contrast, on northern slopes, vegetation slows runoff and promotes infiltration, facilitating the downward leaching of salts from the surface layer. These processes were also observed to be characteristic of the study district.

In the central part of the district, the terrain is very gentle, with an average slope of only 1.5°, whereas in the Aktau Range, slopes can be as steep as 54° (Figs. 4-5). Soil types in Kattakurgan district vary significantly due to geological structure, geomorphology, hydrology, and climate, which in turn influence the spatial variability of salinization. The area is dominated by brown and gray soils (Fig. 6).

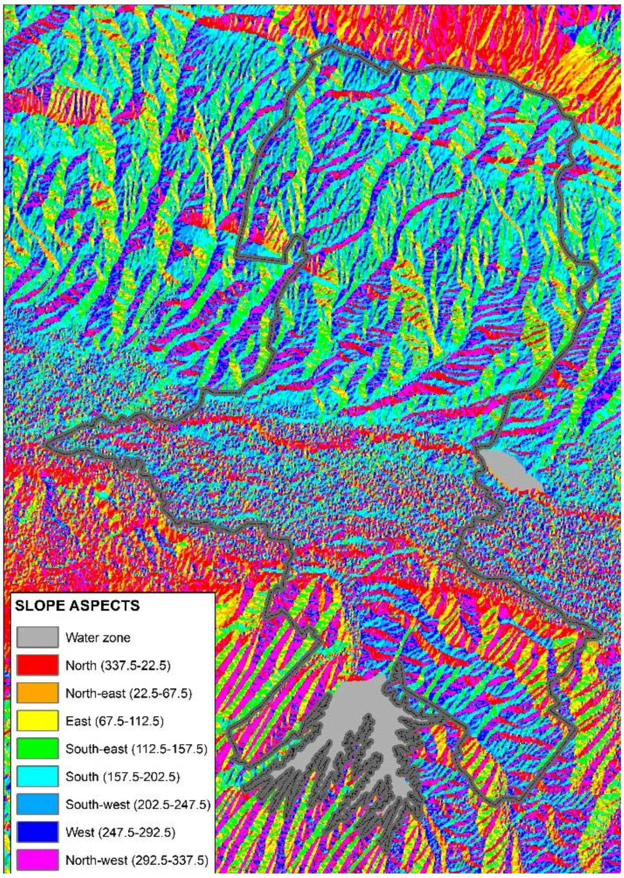

Figure 4. Slope aspect map of Kattakurgan district

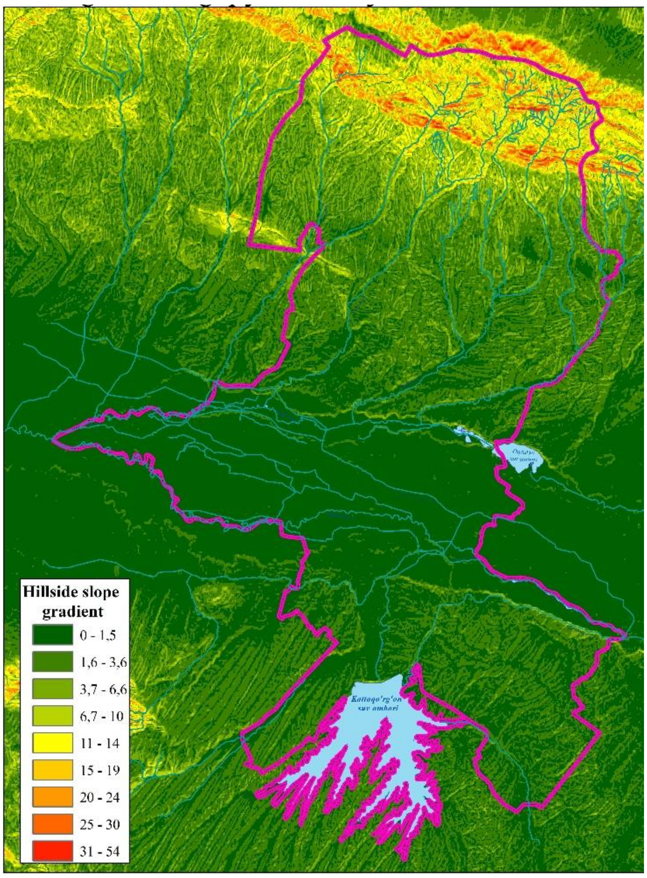

Figure 5. Slope gradient map of the slopes in Kattakurgan district

Brown soils (marked as 1 on the map in Fig. 6) are located in piedmont areas, with strong slope erosion, high skeletal content, and weak carbonate presence. These soils are well-drained, have low water retention, and are highly resistant to salinization. Thus, these zones are low-risk areas for salinization because the steep terrain and rapid water flow prevent salt accumulation.

Gray soils (marked as 2 on the map in Fig. 6) are moderately to strongly eroded and contain coarse skeletal material. These soils exhibit favorable physical properties, strong drainage, and low water retention, making them similarly resistant to salinization. Salts do not rise to the surface, and water infiltrates into deeper layers, limiting surface salinity.

In most parts of the district, typical gray soils dominate, which are classified into 16 types based on erosion, skeletal content, carbonate presence, sandiness, and reclamation status [19]. This is the largest soil area in the region and also the site where salinization processes are most active. These soils are generally sandy to moderately sandy, which facilitates rapid water percolation. In many locations, a gravel layer exists

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at a depth of 0.5–1 m, causing irregular groundwater levels. Some of these soils have a history of irrigation, while others are newly developed. Additionally, weak to moderate salinization is observed in many areas.

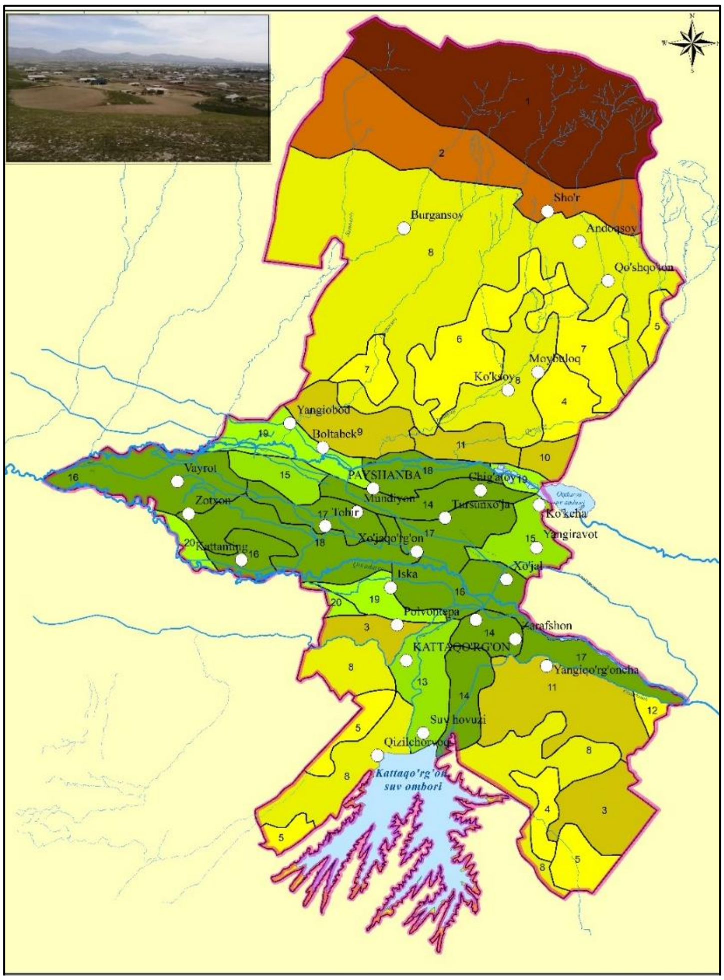


Figure 6. Soil map of Kattakurgan district (authors' compilation)

Newly irrigated typical gray soils (marked as 3, 9, 10, and 11 on the map in Fig. 6) are recently developed reclamation areas. Due to the presence of gravel layers, water drains rapidly, but infiltration is uneven and water loss is substantial. Consequently, capillary rise of salts accelerates under new irrigation, increasing the risk of salinization.

Non-irrigated (rainfed) typical gray soils (marked as 4, 5, 6, 7, and 8 on the map in Fig. 6) are characterized by low rainfall, high evapotranspiration, and limited water availability, which deepen the aeration zone. As a result, soil salinization does not develop extensively, though salt accumulation may occur during drought years.

Salinized gray-steppe and steppe soils (marked as 12–19 on the map in Fig. 6) represent the primary salinization hotspots in the district. These soils are formed along elevated groundwater zones, river terraces, and adjacent areas. Their composition, often of steppe and alluvial origin, results in a denser soil structure. In irrigated areas, strong capillary rise occurs, and the 0.5–1 m gravel layer limits downward moisture infiltration, further promoting salinization.

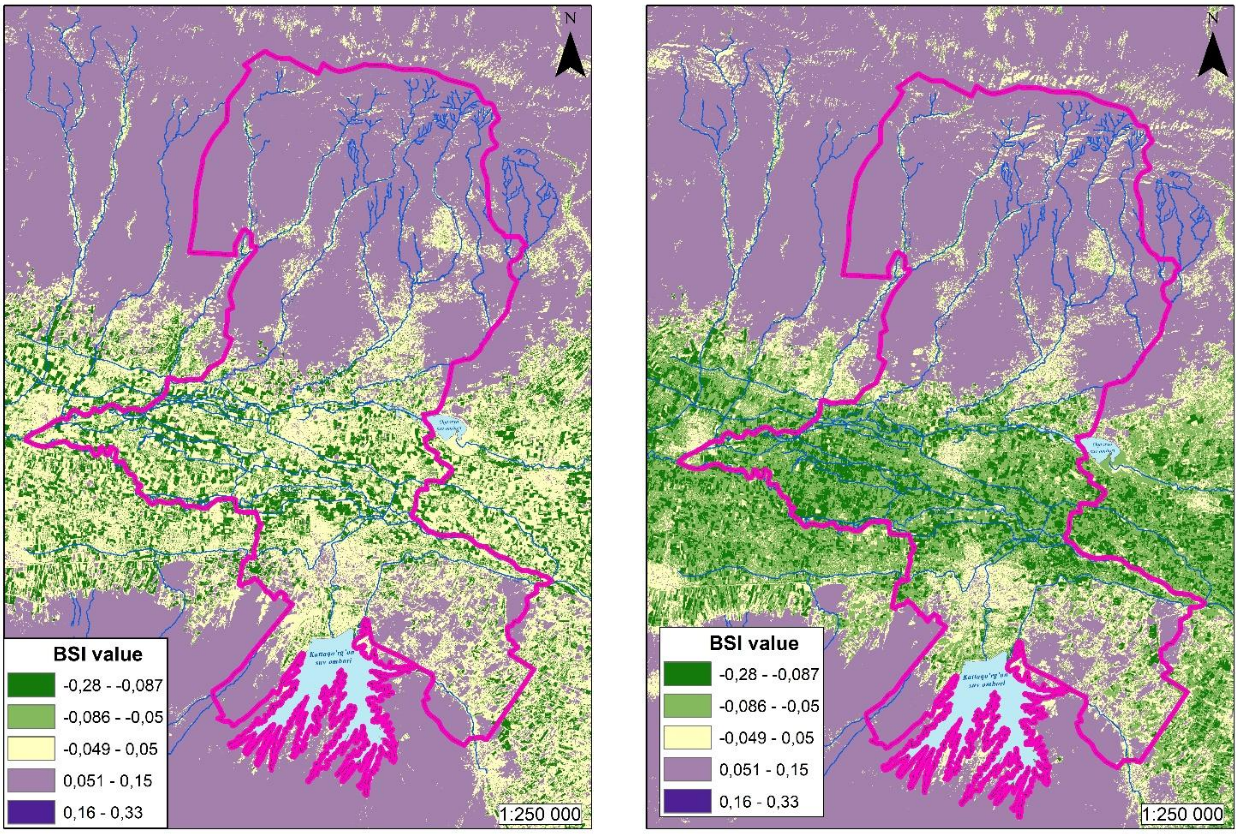
The light-colored gray soil area (marked as 20 on the map in Fig. 6) represents the most problematic soil type in the district, exhibiting moderate to severe salinization. These soils have recently been subjected to irrigated agriculture and are of alluvial origin, containing interlayers of gravel. Salinization is particularly intense here because groundwater is relatively shallow, drainage is poor, and evaporation rates are high.

In recent years, soil salinization, which is increasing in extent and occurring on a global scale, has become a critical issue and an important field for research. Many researchers have analyzed soil salinization using various methodologies based on remote sensing techniques. In particular, Landsat Collection 2 Level-2 8/9 OLI/TIRS imagery is widely employed for such studies. As is well known, these images contain 11 spectral bands used for measuring different parameters. Among them, the bands most indicative of soil salinity are blue (B), red (R), near-infrared (NIR), and shortwave infrared (SWIR1), as these wavelengths effectively reveal the saline surface of soils. However, other indices and parameters are also important for accurately assessing salinization.

One of the earliest approaches in this field was developed by Rikimaru and Miyatake (1997), who proposed the Bare Soil Index (BSI) to identify exposed soils. This method has since been widely applied by numerous researchers [13]. For creating such maps, spectral bands 2, 4, 5, and 6 are typically used (2):

$$BSI = \frac{(\mathrm{SWIR1} + \mathrm{Red}) - (\mathrm{NIR} + \mathrm{Blue})}{(\mathrm{SWIR1} + \mathrm{Red}) + (\mathrm{NIR} + \mathrm{Blue})} \tag{2}$$

The resulting Bare Soil Index (BSI) values range from –1 to +1. Values closer to –1 indicate that the soil surface is either highly moist or densely covered with vegetation. Conversely, values approaching +1 signify exposed soil surfaces with little to no vegetation and minimal surface moisture, directly reflecting soil-driven evapotranspiration. Consequently, areas with high BSI values can be interpreted as zones susceptible to salinization. The BSI map for Kattakurgan district was also generated (Fig. 7). To ensure accurate and reliable data, it is advisable to select periods with clear skies and minimal precipitation; therefore, July was chosen for this analysis.



July September

Figure 7. Bare Soil Index (BSI) map of Kattakurgan district

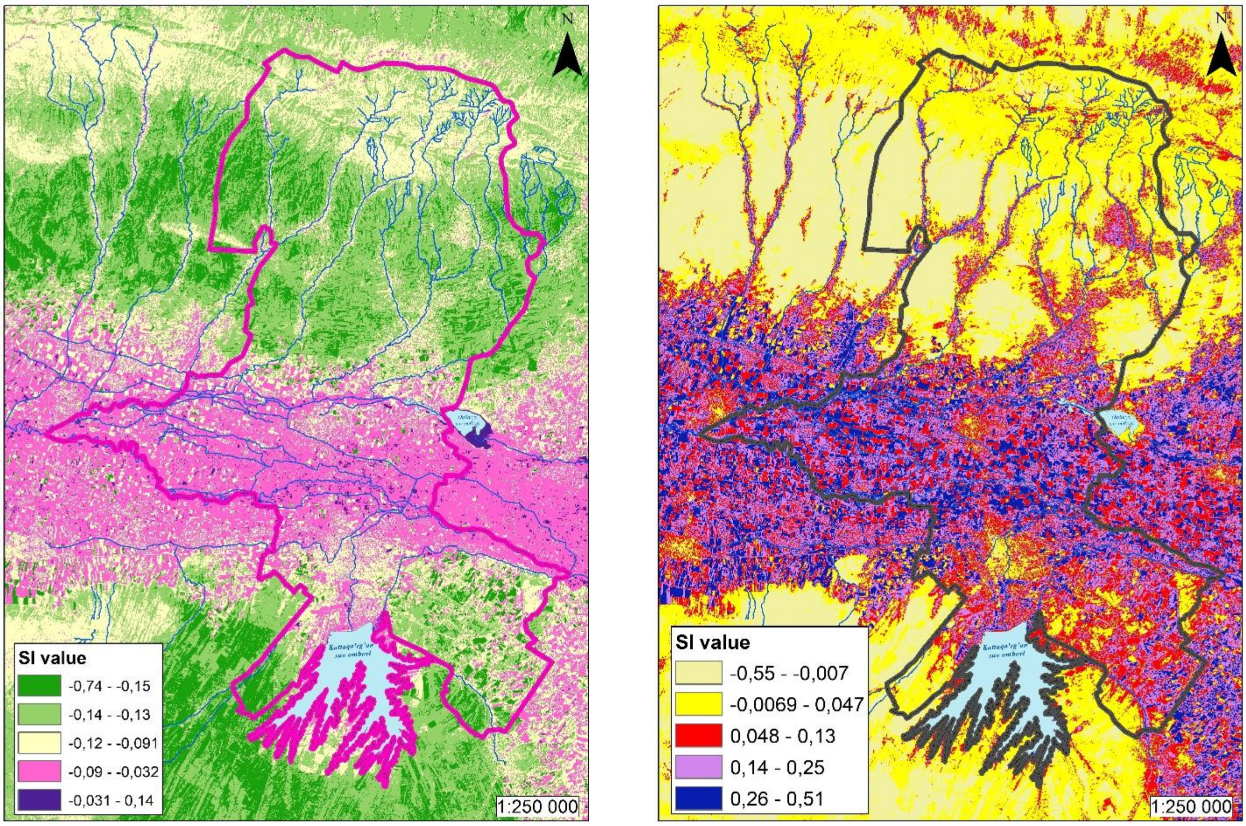
According to this index, in July, the majority of the district exhibits exposed soil surfaces. Only in cultivated areas, particularly cotton fields, does the soil retain moisture and support vegetation growth. Consequently, relatively vegetated areas are primarily observed along rivers and streams, where water resources are available. By September, due to the decrease in temperature compared to July, the extent of exposed soil surfaces is reduced. Additionally, while cotton fields were not fully green in July, they reach full maturity by September.

In summary, the BSI allows the identification of potential salinization zones in the northern and southern parts of the district. However, it should be noted that this index provides information only about the soil surface layer.

For assessing soil salinity, the Salinity Index (SI) is also widely used. There are more than ten variants of this index [3; 13; 15-16]. The most commonly applied version is calculated as the ratio of the red to near-infrared spectral bands multiplied by 100 [15]. The most frequently used formulas for this index are presented below (3, 4):

$$SI = \frac{Blue - Red}{Blue + Red} \quad (3) \qquad \text{or} \qquad SI = \frac{\mathrm{NIR} - \mathrm{SWIR}}{\mathrm{NIR} + \mathrm{SWIR}}. \quad (4)$$

This method also represents a surface-based indicator, meaning that it reflects salinity only in the topsoil and does not detect salinization occurring in deeper soil layers. When the salinity index map was generated for Kattakurgan district, it was found that the soils across the area generally exhibited low to moderate salinity (Fig. 8). Moreover, higher salinity index values were observed in the typical gray soils under irrigated agriculture. Similar to the BSI, the SI values range from –1 to +1, where values closer to +1 indicate stronger salinization, while values near –1 correspond to moist soil or areas covered with vegetation.



3 4

Figure 8. Soil Salinity Index (SI) map of Kattakurgan district (compiled by the authors based on remote sensing data)

Another index used for assessing soil salinization is the Normalized Difference Salinity Index (NDSI) (5) [3; 16-17], also referred to as the Normalized Difference Soil Index (NDSI) (6). Although these methods, like the SI, are among the most widely applied formulas, different researchers employ them in varying ways for salinity assessment [23-24].

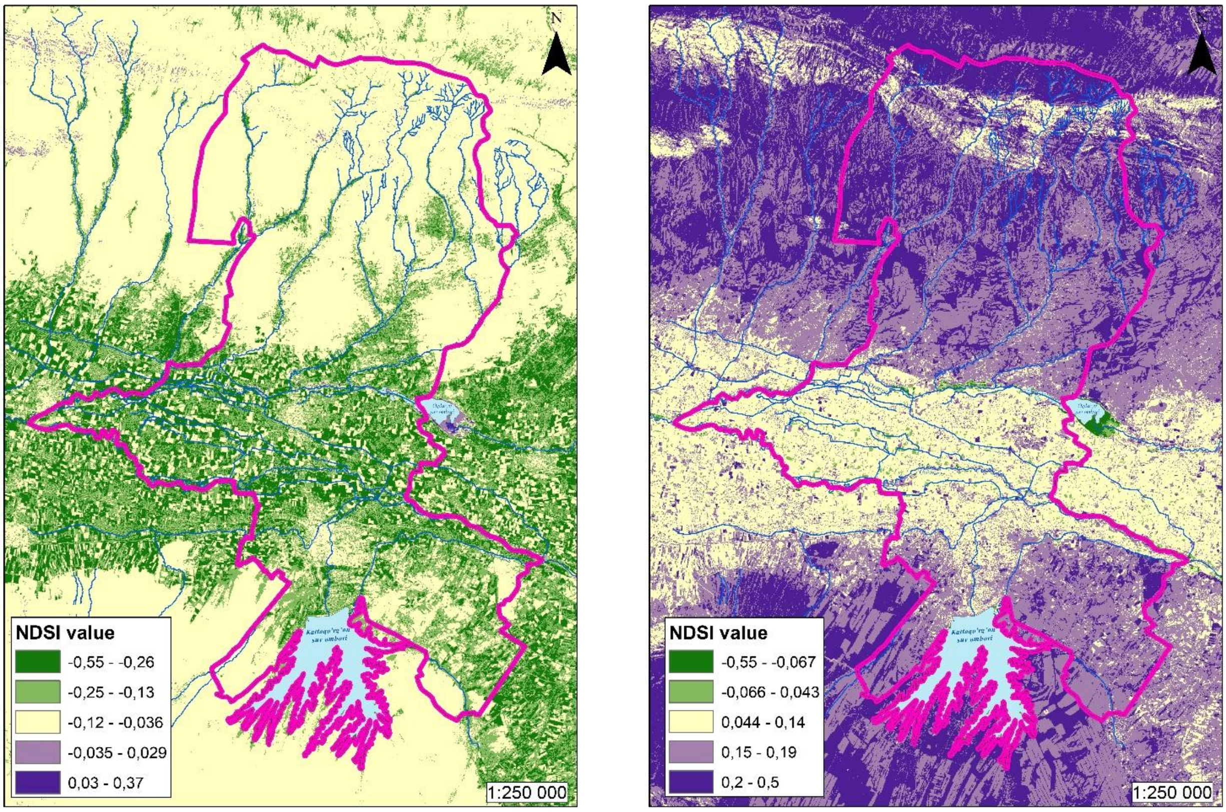
$$NDSI = \frac{\mathrm{Red} - \mathrm{NIR}}{\mathrm{Red} + \mathrm{NIR}} \quad (5) \qquad NDSI = \frac{\mathrm{SWIR} - \mathrm{Green}}{\mathrm{SWIR} + \mathrm{Green}} \quad (6)$$

Both NDSI formulas were applied to assess soil salinization in the district, and they were represented in two distinct visual formats. In the map analyzed using Bands 4 and 5, non-cultivated areas (light yellow / beige) are clearly distinguished. Irrigated fields (green) are prominently visible, as the NIR band is sensitive to soil moisture and vegetation.

In contrast, the map derived from Bands 6 and 3 highlights dry soils and salinized areas in positive colors (light yellow–white), while vegetated areas and water bodies appear in negative or near-zero values (blue–purple). This is because SWIR1 is sensitive to moisture and salinity, while the Green band responds to soil and vegetation, making this method effective for distinguishing mineral properties of the soil.

Analysis of these maps clearly identified areas used for agriculture along water-rich zones, such as the Karadarya and Akdarya regions. However, in the northern part of the district, within the Aktau Range where the Aktau series prevails and agriculture is not practiced, the map still shows positive values. Comparing this with slope gradient and aspect maps (Figures 4-5) reveals that positive values in these areas correspond to slopes ranging from 15° to 50°, with aspects predominantly north and northwest in some locations.

The analysis of the Normalized Difference Salinity Index (NDSI) also reflected the influence of soil types and underlying gravel layers. Areas with salinized or salinity-prone soils are identifiable on the NDSI map. However, due to the ongoing vegetation period in much of the district during the analysis period, the results were not fully pronounced.



5 **6**

Figure 9. Normalized Difference Salinity Index (NDSI) (5)
and Normalized Difference Soil Index (NDSI) (6) maps of Kattakurgan district

To account for the influence of vegetation during this period, many researchers emphasize the importance of using Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) maps when studying soil salinization via remote sensing [13; 14–16]. For generating these maps, Landsat imagery is employed, with the red band (Band 4) and near-infrared band (Band 5) used for NDVI, and the near-infrared and shortwave infrared bands (Band 6) used for NDMI. The calculation formulas for these indices are widely accepted and consistently applied across studies:

$$NDVI = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \quad (7) \qquad NDMI = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \quad (8)$$

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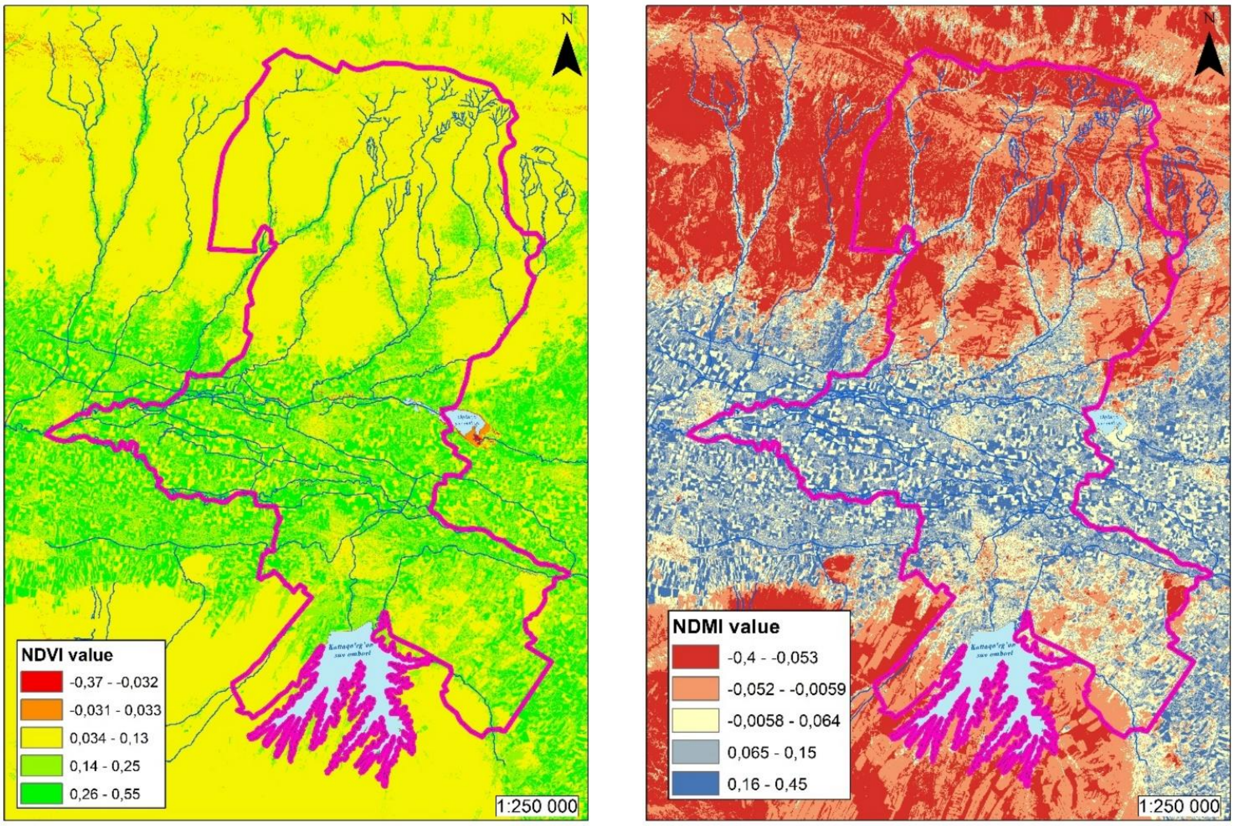
The generation of NDVI and NDMI maps for the Kattakurgan district confirmed the aforementioned scientific observations. In July, a large portion of the area is covered with cultivated vegetation, irrigated through agricultural practices. Additionally, groundwater during this period is relatively shallow, which further increases soil moisture. As a result, despite the presence of soil salinity, salts are not readily visible on the surface due to the reflectance of vegetation or because the minerals dissolve in water and become part of the soil solution.

Comparing the Normalized Difference Salinity Index (NDSI) map with the NDVI and NDMI maps revealed a clear correspondence. Areas indicated as non-salinized on the NDSI map coincide with regions of dense vegetation cover and higher soil moisture levels, confirming the reliability and complementarity of these indices in assessing soil salinity.



7 ***8***

Figure 10. NDVI (7) and NDMI (8) maps of Kattakurgan district

In the Kattakurgan district, the Tasseled Cap Wetness (TCW) method, which identifies vegetation and soil moisture, is considered particularly suitable for assessing soil salinization. TCW can, in some cases, provide a more accurate representation of salinization than NDSI or SI, making it well-suited for the study area. This is because remote sensing analyses have shown that the region exhibits dense vegetation, advanced agricultural activity, extensive irrigated areas, and high soil moisture.

The NDSI, developed for the district, does not effectively reflect soil salinization in areas with dense vegetation, as it is primarily effective in bare soil regions. In contrast, TCW can provide more accurate results in such contexts because it isolates moisture rather than vegetation. Additionally, TCW is highly sensitive to the SWIR bands, which respond to soil moisture, vegetation water content, and signals from saline minerals. Salinized soils exhibit strong absorption and reflectance anomalies in the SWIR spectrum.

Although TCW was first developed in 1984 [25], its application in soil salinity studies and calibration for Landsat 8/9 imagery has been extensively documented, particularly in arid and semi-arid regions by Allbed and Kumar [12]. The TCW results for the district were determined based on these studies (Fig. 9) [12].

$$TCW = 0.1511 \cdot Blue + 0.1973 \cdot Green + 0.3283 \cdot Red + 0.3407 \cdot NIR - 0.7117 \cdot SWIR1 - 0.4559 \cdot SWIR2 \quad (9)$$

According to the TCW results generated for Kattakurgan district, areas with low TCW values (–47,000 to –7,200) represent the most salinity-prone zones of the district, which correspond closely with the NDSI (salinity) indices. Areas with high TCW values are well-irrigated and sufficiently moist, indicating a low risk of salinization.

These results provide information on soil salinization within approximately the top 5–10 cm of the soil surface. If salinization occurs deeper than 10 cm, remote sensing methods may not effectively detect it. Accurate information for deeper soil layers can be obtained through soil profiling and geochemical analyses.

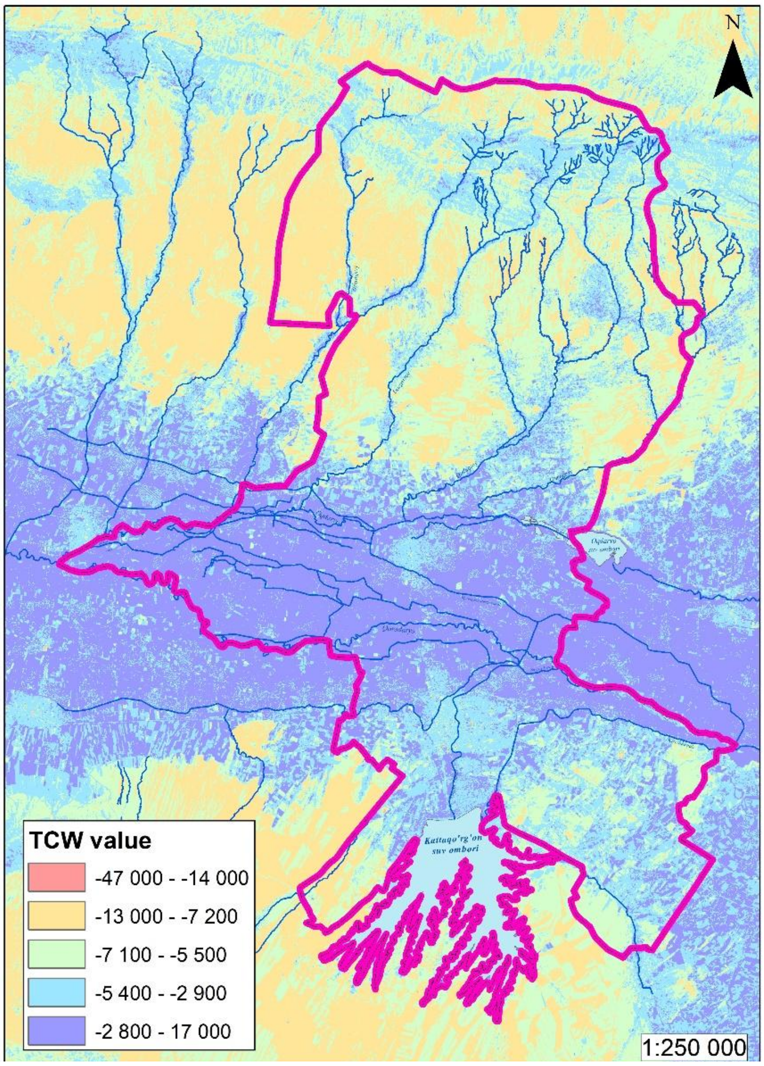


Figure 11. Tasseled Cap Wetness (TCW) map of Kattakurgan district

The GIS- and remote sensing-based analyses of soil salinization in Kattakurgan district provided an opportunity for an in-depth examination of the internal interconnections among natural components, morphological zonation, moisture distribution, salinization processes, and ecological stability. The study integrated geomorphology, hydrogeology, annual precipitation, soil types, slope gradients, and aspect, along with remote sensing indices—Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Tasseled Cap Wetness (TCW), Bare Soil Index (BSI), Salinity Index (SI, two types), Normalized Difference Soil Index (NDSI), and Normalized Difference Salinity Index (NDSI).

1. Influence of geomorphology, slope, and aspect

The district's relief primarily consists of plains and Quaternary deposits, including river terraces, erosion-accumulative terraces, alluvial fans, and flat zones near reservoirs. These landforms directly influence vegetation density and salinization processes. Most of the area has slopes ranging from 0–3°, and the flat relief slows natural drainage, which is clearly reflected in the SI and NDSI (salinity) maps, where the salinized areas are concentrated.

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Aspect maps indicate that north-facing slopes receive less solar radiation, resulting in relatively moister and cooler microclimates. In these zones, NDVI and NDMI values are higher compared to areas with minimal anthropogenic impact, creating favorable conditions for vegetation growth.

2. Soil types and their effect on spectral indices

The district is mainly covered by gray soils, takir soils, and saline soils. Takir soils exhibit high reflectivity and appear with elevated values in BSI and SI results. Saline soils are distinctly identified as bright, whitish textures on NDSI (salinity) maps.

Comparison of soil maps with spectral indices demonstrates that areas with sparse vegetation experience strong salinization. Exposed soils in these areas show high BSI values and SI values ranging from –0.74 to 0.14 or –0.55 to 0.51, depending on the calculation method.

3. Vegetation dynamics (NDVI, NDMI, TCW)

NDVI values across Kattakurgan range from –0.37 to 0.55, indicating moderate vegetation cover. Higher NDVI values (0.14–0.55) are observed near water bodies, while dry and bare zones have lower values.

NDMI values indicate vegetation moisture levels ranging from –0.4 to 0.45, reflecting moderate moisture availability consistent with national climatic conditions.

The TCW index is directly associated with soil salinization in Kattakurgan. Positive TCW values identify hydrated, saline zones with shallow groundwater. Comparison of TCW with NDVI, NDMI, BSI, and SI indices shows that areas with sparse vegetation, exposed soils, and high moisture content constitute the primary salinization zones. TCW results align closely with the hydrogeological basis of salinization in the district (groundwater mineralization, shallow water tables, high evaporation), confirming its reliability as an indicator for remote sensing-based salinity assessment.

4. Salinization processes (SI, NDSI, Normalized Difference Soil Index)

Salinization represents one of the district's most critical ecological issues. SI values range from –0.74 to 0.51: values between 0.05–0.51 indicate strongly exposed soils, significant salinization, and unwashed areas, whereas values below –0.3 correspond to vegetated, moist regions.

The Normalized Difference Salinity Index (NDSI) more precisely highlighted soil salinization and revealed that salinized areas expand with increasing distance from the reservoir. This pattern aligns with hydrogeological conditions, as areas with shallow groundwater experience intense evaporation and, consequently, higher salinity. In some water-adjacent zones, NDSI (salinity) values reached 0.14. Scientifically, these water basins can be associated with:

- ✓ water turbidity,
- ✓ flat and shallow relief,
- ✓ salinization,
- ✓ a mixture of aquatic vegetation.

When all layers are integrated, the Kattakurgan district can be characterized as follows:

- ➢ Vegetation: moderate overall, higher along water bodies.
- ➢ Salinity: strong in central and western parts.
- ➢ Moisture: high near water bodies, low elsewhere.
- ➢ Relief: relatively flat in the central area, with poor drainage.
- ➢ Soils: dominated by mountain brown, takir, and gray soils.
- ➢ Ecological stability: from moderate to low.

These results are scientifically coherent, clearly demonstrating the interrelationship: relief → drainage → soil → vegetation → salinization.

Conclusions

This study was aimed at a detailed analysis of soil salinization in the Kattakurgan district through the integration of GIS technologies and remote sensing indices. The obtained results provided important scientific insights for assessing the ecological condition of the region and for the sustainable management of its natural resources.

1. Key scientific findings

- The NDVI, NDMI, and TCW indices confirmed the presence of moderate vegetation in the district.
- According to the SI, soil salinity (NDSI), and soil type (NDSI) maps, the central parts of the district were found to be highly prone to salinization.

- Water bodies and riparian zones were delineated with high accuracy, demonstrating the seasonal variability of water resources.
- Geomorphological and slope maps confirmed that in flat areas of the district, natural drainage is slow, which intensifies salinization processes. Conversely, areas with steep slopes do not favor salt accumulation due to rapid leaching.

2. Scientific and practical significance of the study

- The integrated use of remote sensing indices allowed the creation of a digital ecological passport of soils in the Kattakurgan district.
- The results can serve as a basis for reclamation measures, agricultural planning, tourism development, and environmental monitoring.
- Integrated soil salinization analysis made it possible to identify areas currently affected by salinization (mainly newly irrigated lands) and areas potentially at risk in the future.

The application of remote sensing data in the Kattakurgan district provided high scientific and practical results in identifying, assessing, and mapping soil salinization processes. BSI, SI, NDVI, NDMI, NDSI (salinity), NDSI (soil), NDMI, and Tasseled Cap Wetness (TCW) indices, derived from Landsat 8-9 satellite images in a GIS environment, accurately reflected the spatial structure of the physical and chemical properties of the soil, moisture content, and salinization processes.

The results indicated that areas with intense salinization were mainly located in zones with takir and gray soils and low vegetation cover (NDVI −0.37–0.05). High BSI and SI values in these areas confirmed the presence of bare soils with low moisture and high salt content. On NDSI maps, saline-alkali fields stood out with bright, whitish textures, clearly showing the landscape signature of salinization processes.

NDMI and TCW indices effectively indicated vegetation and soil moisture dynamics, revealing uneven moisture distribution across the district. TCW values ranged from −47,000 to +14,000, with particularly low values corresponding to dry soils and areas with high salinization risk. NDMI results confirmed that in agricultural lands lacking sufficient moisture, salinization processes intensify.

The study showed that the probability of increased salinization is higher in irrigated areas, zones with relatively high groundwater levels, and areas where water mineralization is moderate. Groundwater levels in the district ranged from 0.8 to 2.7 m, confirming its key role in salinization distribution. Comparison of remote sensing indices with soil maps demonstrated the explanatory relationship between salinization processes and landscape structure.

Practical recommendations based on the study:

1. Intensify reclamation washing in areas with strong salinization;
2. Modernize drainage systems and maintain stable groundwater levels;
3. Enhance agrobiological reclamation using halophyte plants;
4. Apply water-saving irrigation technologies extensively;
5. Establish green protective zones against erosion in open areas with high salinization risk;
6. Regularly use remote sensing indices as monitoring tools.

In general, the study scientifically elucidated the natural-geographical bases of soil salinization in the Kattakurgan district, its formation factors, and the possibilities of detection using modern remote sensing methods. The results have significant practical value for making agrotechnical and reclamation decisions, ensuring ecological sustainability, and increasing agricultural productivity in the district.

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Өзбекстанның аридті аймақтарындағы топырақтың тұздану динамикасын ГАЖ және қашықтықтан зондтау индекстерін пайдаланып кешенді талдау

Зерттеу географиялық ақпараттық жүйелерді (ГАЖ) және Жерді қашықтықтан зондтау индекстерін (ЖҚЗ) пайдалана отырып, Өзбекстанның Қаттықорған ауданындағы топырақтың тұздану процестерін кешенді талдауға арналған. Зерттеулер геоморфология, гидрогеология, жылдық жауын-шашын мөлшері, беткей градиенті, аспекті және топырақ түрлері сияқты табиғи компоненттерді қашықтықтан зондтаудың негізгі көрсеткіштерін біріктіреді, мысалы, өсімдіктердің нормаланған айырмашылық индексі (NDVI), ылғалдың нормаланған айырмашылық индексі (NDMI), шашақты қалпақ ылғалдылығы (TCW), жалаңаш топырақ индексі (BSI), тұздану индексі (SI) және тұзданудың нормаланған айырмашылық индексі (NDSI). ГАЖ ортасында кеңістіктік талдау жүргізу үшін Landsat 8/9 ғарыштық түсірілімдері қолданылды. Сонымен қатар ГАЖ және ЖҚЗ-талдау экологиялық тұрақтылықты бағалау, ирригациялық-мелиорациялық іс-шараларды жоспарлау және су ресурстарын басқаруды оңтайландыру үшін маңызды ақпарат береді. Кешенді тәсіл бастапқы тұздану аймақтарын дәл анықтауға, өсімдіктер мен су экологиялық процестерін бағалауға, сондай-ақ негізделген агротехникалық және мелиоративтік шешімдерді қолдауға мүмкіндік береді. Бұл зерттеу ГАЖ және ЖҚЗ индекстерінің үйлесімі топырақтың тұздануын бақылау және жартылай құрғақ аймақтарда жерді тұрақты басқаруды басқару үшін сенімді және тиімді құрал екенін көрсетеді.

Кілт сөздер: топырақтың тұздануы, ГАЖ, қашықтықтан зондтау, NDVI, NDMI, TCW, BSI, SI, NDSI, аридті аймақ, Қаттықорған ауданы.

М.М. Авезов, А.М. Элмуратова, А.И. Аманжолов

Комплексный анализ динамики засоления почв в семиаридных районах Узбекистана с использованием ГИС и индексов дистанционного зондирования

Данное исследование посвящено комплексному анализу процессов засоления почв в Каттакурганском районе (Узбекистан) с использованием географических информационных систем (ГИС) и индексов дистанционного зондирования Земли (ДЗЗ). Исследования интегрируют природные компоненты, включая геоморфологию, гидрогеологию, годовое количество осадков, градиент склона, аспект и типы почв, с ключевыми показателями дистанционного зондирования, такими как нормализованный разностный индекс растительности (NDVI), нормализованный разностный индекс влажности (NDMI), влажность бахромчатой шляпы (TCW), индекс голых почв (BSI), индекс засоленности (SI) и нормализованный разностный индекс засоленности (NDSI). Для проведения пространственного анализа в ГИС-среде были использованы спутниковые снимки Landsat 8/9. Кроме того, ГИС и РС-анализ предоставляют важную информацию для оценки экологической устойчивости, планирования ирригационно-мелиоративных мероприятий и оптимизации управления водными ресурсами. Комплексный подход позволяет точно определить первичные зоны засоления, оценить растительность и водные экологические процессы, а также поддерживать обоснованные агротехнические и мелиоративные решения. Это исследование демонстрирует, что сочетание индексов ГИС и ДЗЗ является надежным и эффективным инструментом для мониторинга засоления почв и руководства устойчивым управлением землей в полузасушливых районах.

Ключевые слова: засоление почв, ГИС, дистанционное зондирование, NDVI, NDMI, TCW, BSI, SI, NDSI, семиаридный регион, Каттакурганский район.

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