EURASIAN JOURNAL OF ACADEMIC RESEARCH
Innovative Academy Research Support Center
IF = 9.3
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MODERN APPROACHES TO THE ECOLOGICAL ASSESSMENT OF THE CURRENT STATE OF IRRIGATED SOILS IN THE SOUTHERN ARAL SEA REGION (USING THE EXAMPLE OF KHOJEYLI AND KUNGRAD DISTRICTS)

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https://doi.org/10.5281/zenodo.20643814

ARTICLE INFO

Received: 02nd June 2026
Accepted: 08th June 2026
Online: 09th June 2026

KEYWORDS

Ecological assessment, irrigated soils, Southern Aral Sea, soil salinization, remote sensing, GIS, Khojeyli, Kungrad.

ABSTRACT

The Southern Aral Sea region is one of the most ecologically degraded areas due to the drying of the Aral Sea and long-term irrigation practices. This study examines modern approaches for assessing irrigated soils in Khojeyli and Kungrad districts using field data, remote sensing, and GIS techniques. Methods such as salinity indices, spatial interpolation (IDW), and predictive modeling (Markov–CA) were applied to analyze soil salinity and degradation patterns. Results show severe chloride–sulfate salinization and very low humus content (0.3–0.7%) in both districts. Khojeyli is mainly affected by poor drainage and shallow saline groundwater, while Kungrad additionally suffers from salt-dust transport from the Aral Seabed. The study confirms that integrating remote sensing with ground data provides an effective and cost-efficient approach for large-scale soil monitoring. It supports targeted management measures such as drainage improvement, windbreak planting, and halophyte cultivation to mitigate soil degradation.

Introduction. The Southern Aral Sea region has undergone severe environmental change as a result of the rapid desiccation of the Aral Sea and long-term expansion of irrigated agriculture. In Karakalpakstan, particularly in the Khojeyli and Kungrad districts, these processes have led to widespread soil salinization, degradation of soil structure, and a noticeable decline in agricultural productivity. The situation is further aggravated by arid climatic conditions, inefficient drainage networks, shallow and highly mineralized groundwater, and prolonged use of saline irrigation water [4, 207-232]. Although traditional field sampling and laboratory analyses provide accurate information on soil properties, they are not sufficient for regional-scale monitoring due to their limited spatial coverage and high cost. This creates challenges in understanding the full extent and dynamics of soil degradation across large irrigated areas. To address these limitations, modern approaches based on remote sensing, GIS, and spatial modeling have been increasingly applied.

These methods enable continuous monitoring of soil salinity, mapping of affected zones, and integration of field measurements with satellite data for more comprehensive analysis. Accordingly, this study investigates the ecological condition of irrigated soils in Khojeyli and Kungrad districts using integrated geospatial techniques and demonstrates the relevance of modern monitoring tools for effective environmental assessment and land management in the Southern Aral Sea region. [1].

Modern methods integrate in situ measurement data and remote sensing and GIS technologies in order to compensate for drawbacks of traditional approaches. For example, Otenova and Mambetullaeva obtained data by collecting soil samples in layers from 0 to 30cm in the envelope method within the Chimbay and Kegeyli districts [6]. However, these data are only meaningful when used in conjunction with satellite-derived information such as salinity and normalized difference salinity indices (NDSI, SI, BI), as developed using Landsat 8, Landsat 9 and Sentinel 2 imagery, respectively. These remote sensing derived indices are proven to effectively detect salinized soils across Karakalpakstan because salt crust, gypsum and halomorphic soil are highly spectrally reflective at certain wavelengths. The data collected from remote sensing is often superimposed with spatial information such as depth of the groundwater table, texture of the soil, the layout of the irrigation network and land use through GIS (ArcGIS and QGIS) enabling determination of 'hot spots' and causation relationships. For instance, based on IDW interpolation within GIS, a survey performed by Jabbarov and others revealed the extent of extremely and severely saline soil increased significantly over 12 years (2011-2023) in Khojeyli. Specifically, from 8% to 22% of land in the study area was extremely saline (ECe>16dS/m). In order to predict future trends and thus anticipate the dust source area and priority interventions, predictive models like the Markovcellular automata (MarkovCA) are often utilized for simulating future land cover change on the dried Aral seabed. For instance, with no action, predicted barren salinized soil could cover an additional 8-12% by 2030 in Northern Kungrad [2, 1-12].

In the irrigated lands of the southern Aral Sea area, there are several constant and disturbing trends reflected in the scientific literature. First, very low levels of organic matter (humus) are found, in most cases ranging from 0.3-0.7% in the topsoil layer (0-30cm). This is due to arid conditions (high temperature and high evapotranspiration), low biomass input, and decades of intensive agriculture without application of manure or compost. As a result, soil structure is fragile, crusted, with low infiltration and poor aeration. Second, salinity is the dominant type of degradation. Analysis of water extracts from soil samples (soil-water ratio 1:5) constantly shows that the most characteristic type of water is chloride-sulfate water. The main toxic component of chlorides is the chloride ion, with detrimental effects on the plants at concentrations higher than 10-15 meq/L and characteristic leaf burning and specific ion toxicity. Sulfates are less toxic but contribute to increased osmotic stress and reduced water uptake and can promote collapse of the soil structure in association with sodium. Furthermore, secondary salinization is also aggravated by irrigation water containing dissolved salts from the Amu Darya (in low flow season, from 2 to 3 g/L of TDS), and shallow groundwater (usually 1 to 2 m depth) with high salinity. Salts are drawn to the surface by capillary action, and deposited in the root zone, accumulating by evapotranspiration [3, 5-8].

In the two districts there are some differences in their degradation processes. In the district of Khojeyli, lying to the left of the Amu Darya River and having fairly good irrigation systems, the issue of inadequate drainage prevails. According to Jabborov and others, the depth of groundwater level in field survey ranges between 1.2-1.8m with mineralization 5-8 g/L, causing high capillary rise, and thus salinization of soil profile, especially during summer high evapotranspiration rate (more than 1,500 mm). During the period from 2011 to 2023, the percentage of strongly saline soils (ECe > 8-16 dS/m) increased by 18%, extremely saline soils (ECe > 16 dS/m) were transformed from small spots to contiguous zones covering almost a quarter of the irrigated area. In Kungrad district, north of it and nearest to the receding shoreline of the Aral Sea (30-50 km away), besides salinization by groundwater, there is additional problem: salt-dust storms from the bottom of the Aralkum desert [2, 1-12]. This area is about 5 million ha and there are about 10 billion tones of salts on the former seabed. The dust particles in storms are carried by the wind (which usually is faster than 10-15m/s) high up in the air (1-2 km altitude) up to several hundred kilometers away. These particles then fall back on the cultivated areas and increase soil salinity from the top. This is why soil salinization of this district can't be assessed without taking into account of salt-dust storm effects. Remote sensing techniques, like MODIS and Landsat imagery have been used for mapping dust distribution over the farmlands seasonally. According to Minashkina et al., dust concentration over cultivated lands reaches highest values in spring (March to May) and autumn (September to November) when wind speeds are at their maximum and soil conditions on the seabed are the driest [5].

Below is a simplified table that illustrates some of the most important ecological indicators and current methods for assessing them in both districts:

Table 1

Comparative ecological indicators of irrigated soils in Khojeyli and Kungrad districts

Indicator	Khojeyli District	Kungrad District
Main salinization type	Chloride-sulfate	Chloride-sulfate + aeolian salt
Salinity trend (2011–2023)	Strongly increasing (severely saline areas up ~18%)	High, with spikes after dust storms
Key degradation driver	Poor drainage + shallow saline groundwater	Dust storms from dried Aral seabed

Organic matter (humus)	Very low (0.4–0.7%)	Very low (0.3–0.6%)
Main modern assessment method	GIS + field salinity mapping	Remote sensing + dust trajectory models

These techniques allow managers to implement localized actions specific to each district's situation. For example, in Khojeyli, a GIS-based salinity map helps in prioritizing the fields for leaching (an excess water treatment used to flush salts out of the root zone) and planning an appropriate subsurface drainage system. High-salinity-tolerant, indigenous species such as the saxaul (Haloxylon aphyllum) and tamarisk (Tamarix ramosissima) are used as windbreaks for Khojeyli based on similar maps; these trees contribute to lowering the ground water level through their high transpiration rates and capture windblown dusts thereby reducing salt accumulation in the surrounding fields. In a pilot project at Khojeyli where such windbreaks were established the topsoil salinities were reduced by 25–30% within 3 years. In Kungrad, models of dust trajectories together with remotely sensed imagery are used to forecast future dust sources and optimal positions for windbreaks. New windbreak plantings were encouraged for the region with these maps. Also, for more affected fields, a change in land use is suggested for halophyte cultivation (e.g., Salicornia europaea, Kalidium caspicum), because they can be grown on saline land and their biomass can be used for animal feed, biofuel, and perhaps pharmaceutical purposes. For example, trials withhalophyte cultivations in the region yielded a biomass productivity of 5–8 ton/ha on highly saline soil and can represent an additional revenue for the farmers [7, 21-26].

Despite these improvements in our ability to analyze large areas, the widespread adoption of modern tools still faces obstacles. In general, it will require ongoinggroundtruthingto validate and calibrate satellite indices-as spectral indices can become misleading due to variations in soil moisture, surface roughness, vegetative cover, and the presence of gypsum or carbonates unless periodic ground verification is performed (e.g., 5-10% of the area is sampled each year). Moreover, the local soil monitoring organizations in Karakalpakstan have only limited technical and financial resources. Few laboratories at the district level are equipped with instruments for rapid and high-throughput measurement (portable EC meters, GPS-integrated field measurement kits), and GIS/remote sensing training is scarce. Additionally, despite decreasing prices, the cost of commercial satellite imagery is still an obstacle for frequent monitoring. Despite the challenges, the evidence points strongly toward the use of remote sensing and GIS as an economical supplement to groundbased surveys. For example, while a three month field campaign on only 10% of Kungrad's irrigated area (approx. 2000ha) would cost tens of thousands of dollars, a remote sensing-GIS survey across the entire district (over 20,000ha irrigated land) can be completed within weeks for

$5,000–$8,000 for imagery and software, although this would be at the cost of absolute precision. A hybrid approach where satellite data are used to broadly scan the area, and targeted ground samples are used to validate remote sensing findings, represents the most viable option for Khojeyli and Kungrad. Support programs, like those provided by the United Nations Development Programme, World Bank, and Central Asian Water and Energy Program, could help speed the transfer of these technologies.

Conclusion. Irrigated soils at Khojeyli and Kungrad are severely degraded and characterize a chloride-sulfate salinization regime with extremely low humus content (< 0.7%). Modern tools like remote sensing, GIS, spatial interpolation (IDW, Kriging) and simulation modeling (Markov CA) provide powerful and economical tools for assessing spatial and temporal trends in these soil properties. Our findings indicate that two different drivers of degradation are at play in Khojeyli and Kungrad, and our recommended solutions are specifically targeted to each: in Khojeyli the primary management options revolve around drainage improvement and windbreak planting; in Kungrad monitoring of dust transport along with the potential for cultivating halophytes provides potential solutions.

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