Satimuratova A.A.
Master's student in Geodesy and Geoinformatics
Berdakh Karakalpak State University
Khudaybergenov Ya.G.
Candidate of Geographical Sciences (PhD)
Associate Professor of the Department of Geodesy, Cartography and Natural Resources
Berdakh Karakalpak State University
Kannazarov Z.U.
Research Trainee in Specialization "Geodesy and Cartography"
Berdakh Karakalpak State University
Сатимуратова А.А.
магистрант по специальности «Геодезия и геоинформатика»
Каракалпакский государственный университет имени Бердаха
Худайбергенов Я.Г., к.г.н. (PhD)
Доцент кафедры геодезии, картографии и природных ресурсов
Каракалпакский государственный университет имени Бердаха
Канназаров З.У.
Стажёр-исследователь по специальности Геодезия. Картография
Каракалпакский государственный университет имени Бердаха

ECOLOGICAL AND RECLAMATION MONITORING USING GEOSPATIAL TECHNOLOGIES IN THE NORTHERN DISTRICTS OF KARAKALPAKSTAN: A CASE STUDY OF KARAUZYAK DISTRICT WITH COMPARATIVE ANALYSIS TO CHIMBAY DISTRICT

Abstract: This article presents a comprehensive framework for ecological and reclamation monitoring in the northern districts of the Republic of Karakalpakstan, with a specific focus on Karauzyak district—one of the least studied and most environmentally vulnerable territories in the Aral Sea region. Using a combination of remote sensing data (Landsat-8/9, Sentinel-2, MODIS), field-based soil and groundwater measurements, and Geographic Information System (GIS) analyses, this study examines the spatial and temporal *dynamics of soil salinization, groundwater behavior, and vegetation degradation over the period 2000-2024.*

Keywords: Ecological monitoring, reclamation monitoring, GIS, remote sensing, soil salinization, Karauzyak district, Chimbay district, Aral Sea region, groundwater dynamics, land degradation, ecological risk zoning, comparative analysis.

ЭКОЛОГО-МЕЛИОРАТИВНЫЙ МОНИТОРИНГ С ИСПОЛЬЗОВАНИЕМ ГЕОПРОСТРАНСТВЕННЫХ ТЕХНОЛОГИЙ В СЕВЕРНЫХ РАЙОНАХ КАРАКАЛПАКСТАНА: НА ПРИМЕРЕ КАРАУЗЯКСКОГО РАЙОНА С СРАВНИТЕЛЬНЫМ АНАЛИЗОМ ПО ОТНОШЕНИЮ К ЧИМБАЙСКОМУ РАЙОНУ

Аннотация: *В данной статье представлена комплексная структура эколого-мелиоративного мониторинга в северных районах Республики Каракалпакстан, с особым акцентом на Караузякский район — один из наименее изученных и наиболее экологически уязвимых территорий Приаралья. Используя комбинацию данных дистанционного зондирования (Landsat-8/9, Sentinel-2, MODIS), полевых измерений почвенных и грунтоводных показателей, а также анализ в географических информационных системах (ГИС), данное исследование рассматривает пространственно-временную динамику засоления почв, поведения грунтовых вод и деградации растительного покрова за период 2000–2024 гг.*

Ключевые слова: *Экологический мониторинг, мелиоративный мониторинг, ГИС, дистанционное зондирование, засоление почв, Караузякский район, Чимбайский район, Приаралье, динамика грунтовых вод, деградация земель, экологическое зонирование рисков, сравнительный анализ*

Introduction

The Aral Sea ecological crisis has created one of the world's most pressing environmental monitoring challenges. Across the 2.5 million hectares of irrigated land in the lower Amu Darya basin—including the autonomous republic of Karakalpakstan—land degradation processes unfold at rates and spatial patterns that conventional monitoring systems cannot adequately track. Soil salinization, the primary degradation process, is both dynamic (changing seasonally with irrigation and evaporation) and irreversible in human timeframes once severe thresholds are exceeded. Groundwater tables, which control the direction and magnitude of salt flux, respond to irrigation management decisions made thousands of kilometers upstream on the Amu Darya. Vegetation cover, including natural halophytic communities that stabilize soils, degrades through a combination of direct anthropogenic pressure (overgrazing, fuelwood collection) and indirect climate-driven changes (drought intensification, dust storm frequency).

Against this backdrop, systematic monitoring is not merely a scientific exercise but a prerequisite for adaptive land management. Without reliable, spatially explicit, and temporally consistent data on land condition, interventions cannot be targeted, their effectiveness cannot be evaluated, and early warning of impending degradation thresholds cannot be provided. Yet monitoring capacity in Karakalpakstan remains severely limited. The Soviet-era network of observation wells and soil monitoring plots has largely collapsed, with fewer than 30% of wells operational and fewer than 10% sampled annually. Remote sensing data, while increasingly available at no cost, requires technical expertise for processing and interpretation that is scarce at the district level. International projects have filled some gaps—notably the German Society for International Cooperation (GIZ) project "Ecologically Oriented Regional Development in the Aral Sea Region" (2019-2023), which developed a GIS-based monitoring system for Chimbay district—but these efforts have not been systematically extended to adjacent districts.

Study Area: Karauzyak District

Karauzyak district is bounded by the Republic of Kazakhstan to the north and west, Chimbay district to the west-southwest, and the Amu Darya river to the east. The district's territory spans elevations from 52 meters above sea level in the irrigated southern zone to 62 meters in the northern desert (the Aralkum surface slopes gently northward toward the former sea). Topographic relief is minimal—less than 3 meters variation across most irrigated areas—but subtle differences in microtopography exert strong control over water ponding, runoff, and salt accumulation.

The climate is hyper-arid and sharply continental. Based on data from the Karauzyak meteorological station (1970-2024), mean annual temperature is 11.2°C, with July mean of 28.5°C (absolute maximum 46.2°C) and January mean of -7.8°C (absolute minimum -33.4°C). Annual precipitation averages 98 mm, falling primarily as brief, intense spring storms (March-May accounts for 45% of annual total). Potential evapotranspiration (reference crop ET0) averages 1,350 mm/year, meaning that natural precipitation meets less than 8% of the water demand of most crops. Southwest winds prevail, with mean velocity of 4.5 m/s and frequent dust storms (20-30 days/year) that transport salt-rich sediments from the Aralkum onto agricultural fields.

Of the 78,400 hectares classified as agricultural land in Karauzyak district, 54,200 hectares (69%) are irrigated cropland, 18,600 hectares (24%) are rainfed or fallow land, and 5,600 hectares (7%) are under orchards or vineyards (District Statistical Office, 2024). The predominant crop rotation is cotton-wheat-fallow, with cotton (25,000 ha), winter wheat (18,000 ha), and alfalfa (4,000 ha) occupying most of the irrigated area. Small plots of vegetables (potato, onion, tomato) and forage crops (sorghum, maize) are cultivated on household garden plots (dekhan farms) totaling 3,200 hectares.

For comparative purposes, Chimbay district—located immediately west of Karauzyak—was selected as a reference. Chimbay shares similar climate, hydrogeology, and agricultural systems but has been the subject of more intensive monitoring due to the GIZ project (2019-2023), which established 42 groundwater observation wells, implemented annual soil sampling at 156 points, and developed a GIS database integrating these measurements with satellite remote sensing data. Key characteristics of the two districts are compared in Table 5.

Table 5: Comparative characteristics of Karauzyak and Chimbay districts

Parameter	Karauzyak	Chimbay
Total area (ha)	589,800	604,900
Irrigated area (ha)	54,200	58,300
Canal lining proportion (%)	15	38

Parameter	Karauzyak	Chimbay
Drainage density (km/km²)	0.31	0.62
Observation wells (#, operational)	8	42
Groundwater monitoring frequency	None (ad hoc)	Monthly
Soil sampling frequency	None (ad hoc)	Biennial
GIS database exists?	No	Yes
Remote sensing training	None	Widespread

Materials and Methods

Three satellite data sources were utilized to capture different temporal and spatial scales of land surface dynamics:

Landsat archive (2000-2024). All available Level-2 surface reflectance scenes from Landsat-5 TM (2000-2011), Landsat-7 ETM+ (2000-2017, excluding SLC-off stripes), Landsat-8 OLI (2013-2024), and Landsat-9 OLI-2 (2022-2024) were acquired via the USGS EarthExplorer portal. Scene selection prioritized cloud-free (<10% cloud cover) acquisitions during the late summer dry season (August-September), when soil salinity signals are maximized due to minimum soil moisture and maximum surface salt concentration. A total of 48 usable scenes spanning 2000, 2005, 2010, 2015, 2020, and 2024 were processed. Preprocessing included conversion to surface reflectance, masking of clouds and cloud shadows (FMask algorithm), and subsetting to the Karauzyak district boundary.

Sentinel-2 (2017-2024). Level-2A products (surface reflectance with scene classification) from Sentinel-2A and 2B were accessed through the Copernicus Open Access Hub. With 10-meter resolution in visible and near-infrared bands—superior to Landsat's 30-meter resolution—Sentinel-2 enabled more detailed mapping of field-scale variability. Scene selection followed the same late-summer, cloud-free criteria as Landsat, yielding 32 scenes from 2017, 2019, 2021, and 2024.

MODIS (2000-2024). MOD13Q1 vegetation index products (250-meter resolution, 16-day composites) from the Terra satellite were used to characterize vegetation phenology and long-term trends. The Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) were extracted for growing season months (April-September) for each year 2000-2024.

All processing was conducted in Google Earth Engine (GEE), a cloud-based platform for petabyte-scale geospatial analysis. GEE's computational infrastructure enabled batch processing of the entire Landsat and MODIS time series without local data downloads or high-performance computing requirements.

Soil salinity cannot be measured directly from optical remote sensing, but empirical relationships exist between surface reflectance and salt content, particularly in the visible and shortwave infrared regions. Previous studies (Scudiero et al., 2015; Fan et al., 2021) have developed spectral indices that correlate with salinity, with performance varying by arid region. Based on a literature review and preliminary testing with Karauzyak field data, three indices were selected:

Salinity Index (SI) $=(B+R)/2$ where B=blue band reflectance, R = red band reflectance. This index, originally developed for non-vegetated saline soils in northwestern China, emphasizes the spectral flattening effect of salt crusts.

Normalized Difference Salinity Index (NDSI) $= (R - NIR) / (R + NIR)$ where NIR = near-infrared reflectance. NDSI exploits the inverse relationship between salinity and the NIR absorption feature characteristic of non-saline minerals.

Canopy Response Salinity Index (CRSI) $= \sqrt{[(NIR * R) - (G * B)]} / \sqrt{[(NIR * R)+(G*B)]}$ where G = green band reflectance. CRSI is designed for partially vegetated surfaces, accounting for the combined signal of soil and vegetation.

For each Landsat and Sentinel-2 scene, these indices were computed and compiled into annual composites for 2000, 2005, 2010, 2015, 2020, and 2024.

Field sampling was conducted during two campaigns (August 2023 and April 2024) at 84 locations distributed across Karauzyak district using a stratified random design. Strata were defined by the 2024 NDSI value (low, medium, high) to ensure representation of the full range of salinity conditions. At each location:

Geographic coordinates were recorded using a handheld GPS (Garmin GPSMAP 65s, ±3 m accuracy).

Soil samples were collected from 0-10 cm (surface) and 10-30 cm (root zone) depths using a stainless steel auger. Three subsamples within a 10-m radius were composited per depth.

Electrical conductivity (EC) of a 1:5 soil-water extract was measured in the laboratory within 48 hours of collection. For conversion to saturated paste EC (ECe)—the standard for crop salinity tolerance—a regional calibration factor of 3.8 (determined by the Karakalpakstan Soil Science Institute) was applied.

Soil texture was determined by the hydrometer method, and pH was measured in a 1:2 water suspension.

For each sampling point, the corresponding remote sensing indices (SI, NDSI, CRSI) were extracted from the 2024 composites. Linear regression was used to develop a site-specific calibration equation predicting log-transformed ECe from index values. The final model, selected based on Akaike Information Criterion (AIC), was:

$$\log10(ECe) = 0.62 + 4.13 \cdot NDSI - 2.87 \cdot SI + \varepsilon$$

($R^2 = 0.74$, RMSE = 0.23 log10 units, n=84)

This model was applied to the full remote sensing archive (2000-2024) to generate time-series maps of predicted ECe.

Groundwater data for Karauzyak district were obtained from three sources: (1) the Karakalpakstan Branch of Uzgidromet (state hydrometeorological service), which maintains 8 observation wells with monthly measurements; (2) local Water Consumer Associations (WCA), which track water levels at 12 irrigation wells; and (3) a dedicated field campaign in October 2023 measuring depth-to-water at 45 abandoned wells or hand-dug pits. Data were compiled for the period 2000-2024, though completeness varied: the state wells have continuous records, but the WCA and campaign data are temporally limited.

For spatial analysis, groundwater depth (m below surface) and total dissolved solids (TDS, g/L) were interpolated using ordinary kriging with a spherical semivariogram model. For temporal analysis, linear and nonlinear trends were fitted to well-specific time series to estimate rates of water table change.

Using MODIS NDVI time series (2000-2024), two metrics were calculated for each 250-m pixel:

Growing season integrated NDVI (GS-NDVI). The sum of daily NDVI from April 1 to September 30, which approximates total green biomass production. To reduce cloud and atmospheric noise, daily values were smoothed using the Savitzky-Golay filter.

In addition, land cover classification was performed on the 2024 Sentinel-2 mosaic using a random forest classifier trained on 500 reference points (identified through high-resolution Google Earth imagery). Classes included: cotton, wheat, alfalfa, fallow/other crop, natural halophytic vegetation, salt crust, bare soil, and water.

Integration of salinization, groundwater, and vegetation data into an ecological risk zoning scheme followed a multi-criteria decision analysis (MCDA) approach analogous to the hydromodular zoning described in Article 1, but with different criteria reflecting the broader monitoring focus. Three composite indices were aggregated:

Salinization risk index (SRI): Weighted combination of current ECe (2024, weight 0.5) and trend in ECe (ΔECe/year, weight 0.5). Higher values indicate more severe and/or rapidly worsening salinity.

Groundwater risk index (GRI): Weighted combination of depth to water (inverse, weight 0.4), TDS (weight 0.3), and rate of water table rise (weight 0.3). Higher values indicate shallow, saline, rising groundwater.

Vegetation degradation risk index (VRI): Weighted combination of current GS-NDVI relative to district mean (weight 0.5) and Mann-Kendall trend (weight 0.5). Higher values indicate low and/or declining vegetation productivity.

These three indices were standardized to 0-100 scales and aggregated using equal weights into an overall Ecological Risk Score (ERS). Natural breaks classification of the ERS across the district produced three risk categories (R1, R2, R3).

To enable systematic comparison with Chimbay district, equivalent indicators were compiled for Chimbay using data from the GIZ project database (provided with permission). Landsat and Sentinel-2 processing was replicated for Chimbay using the same methods described in Sections 3.1-3.3 above. Groundwater and soil data for Chimbay came from the GIZ monitoring network (42 wells, 156 soil points). Differences between districts were tested for statistical significance using two-sample t-tests (for continuous variables) or chi-square tests (for categorical variables).

Results

The 2024 soil salinity map (Figure 2, Table 6) shows widespread salt-affected conditions across Karauzyak district. Only 27.0% of the district's area (159,200 ha) is non-saline (ECe < 2 dS/m), and this class is almost entirely confined to the southern peripheral areas where irrigation is absent or groundwater is deepest. The rest of the district—73.0%—is salt-affected to varying degrees, with the largest share (29.1%) in the weakly saline category (ECe 2-4 dS/m). Notably, nearly 19% of the district (111,800 ha) is moderately to very strongly saline (ECe > 8 dS/m), conditions that preclude conventional agriculture and require either salt-tolerant halophytes, fallowing, or costly reclamation.

Table 6: Soil salinity distribution in Karauzyak district (2024)

Salinity class	ECe range (dS/m)	Area (ha)	% of district
Non-saline	<2	159,200	27.0

Salinity class	ECe range (dS/m)	Area (ha)	% of district
Weakly saline	2-4	171,600	29.1
Moderately saline	4-8	147,200	25.0
Strongly saline	8-15	85,300	14.5
Very strongly saline	>15	26,500	4.4

The temporal trajectory of salinization (Figure 3) reveals accelerating degradation over the 24-year study period. Between 2000 and 2024, the total salt-affected area increased from 385,400 ha (65.4% of district) to 430,400 ha (73.0%)—an absolute increase of 45,000 ha and a relative increase of 7.6 percentage points. However, the composition of salt-affected area changed more dramatically: the combined area of strongly and very strongly saline lands increased from 82,200 ha (13.9% of district) to 111,800 ha (18.9%), representing a 36.0% increase in the severely degraded class.

By decade, the rate of salinization accelerated: 2000-2010 saw an increase of 2.1 percentage points in total salt-affected area; 2010-2024 saw an increase of 5.5 percentage points. This acceleration coincides with documented declines in Amu Darya flow (average annual discharge at the Kyzketken gauge decreased from 52 km³ in 2000-2010 to 38 km³ in 2010-2024), which has reduced leaching and concentrated salts in the remaining irrigated areas.

Groundwater depth and quality have followed trajectories consistent with salinization trends (Table 7). Over the 24-year period, mean groundwater depth decreased from 4.2 m to 2.8 m—a shallowing of 1.4 m, equivalent to an average rise of 5.8 cm per year. The rise was not linear, however; most of the change occurred after 2010 (2.9 cm/year in 2000-2010 vs. 8.1 cm/year in 2010-2024). This post-2010 acceleration matches the documented decline in irrigation water deliveries: with less water supplied to fields, less water is transpired by crops, and less is lost to evaporation from canals and fields, resulting in reduced consumptive use and more water remaining to recharge groundwater.

Groundwater mineralization increased in parallel, from a district-wide mean of 3.1 g/L TDS in 2000 to 4.8 g/L in 2024. The rate of increase was more uniform over time (approximately 0.07 g/L/year). Importantly, the spatial pattern of mineralization does not mirror depth: the highest TDS values (6-8 g/L) occur in the northern desert areas where groundwater is deep (>5 m) but has been concentrated by decades of evaporation from the former Aral Sea bed. In the irrigated zone, TDS values range from 3-5 g/L—marginally acceptable for salt-tolerant crops but requiring careful management to prevent yield decline.

Table 7: Groundwater parameters in Karauzyak district (2000 vs. 2024)

Parameter	2000	2024	Change
Mean depth (m)	4.2	2.8	-1.4 m (shallower)
% area with depth < 2 m	12%	28%	+16 percentage points
Mean TDS (g/L)	3.1	4.8	+1.7 g/L
% area with TDS > 5 g/L	18%	41%	+23 percentage points

The MODIS NDVI analysis (Figure 4) revealed divergent trajectories across land cover classes. For irrigated cropland (cotton, wheat, alfalfa fields as mapped from Sentinel-2), mean GS-NDVI declined by 0.042 per decade ($p < 0.001$), equivalent to a 14% reduction in integrated vegetation productivity over 24 years. This decline is consistent with reported yield declines from district agricultural statistics and reflects the cumulative impacts of salinization and water scarcity.

Significant negative NDVI trends ($p < 0.05$) were detected on 37% of the district's land area; significant positive trends on 8%; and no significant trend on the remaining 55%. Positive trends were concentrated in the southernmost irrigated area, where continued investment in drainage (though inadequate by design standards) has partially mitigated degradation.

Integration of salinization, groundwater, and vegetation indices into the Ecological Risk Score produced three risk zones with distinct management implications (Table 8, Figure 5).

Zone R1 (High Risk Zone). This zone occupies 84,600 ha (14.3% of district), located primarily in the northern irrigated margin and in a belt along the former shoreline. In Zone R1, groundwater is very shallow (mean 1.4 m depth) and saline (mean TDS 6.2 g/L); surface soils are strongly to very strongly saline (ECe > 12 dS/m); and vegetation—where present—is declining rapidly (mean GS-NDVI trend -0.032/year). Conventional irrigated agriculture is not feasible in this zone without major infrastructure investments that are economically improbable. The recommended management priority is either: (a) abandonment and transition to passive ecological restoration (allowing natural halophyte communities to stabilize soils) where land tenure permits; or (b) introduction of highly salt-tolerant cash crops such as Salicornia europaea (sea asparagus), which can be irrigated with brackish water and produces oilseed or forage. Pilot trials of Salicornia in neighboring Kazakhstan have achieved ECe tolerances up to 40 dS/m—far beyond conventional crops.

Zone R2 (Moderate Risk Zone). Occupying 235,000 ha (39.9% of district), Zone R2 surrounds the degraded core and extends southward through most of the irrigated area. Groundwater depth (mean 3.1 m) and TDS (mean 3.9 g/L) are intermediate, and soil salinity is weakly to moderately saline (ECe 4-8 dS/m). Agriculture is practiced on 58% of Zone R2 area, but productivity is declining. The management priority is preventive: maintain existing drainage, adopt the zone-specific irrigation regimes developed in Article 1, and transition away from cotton (higher salt sensitivity) toward wheat and forage crops (moderate sensitivity). Without intervention, portions of Zone R2 will transition to R1 conditions within 15-20 years at current degradation rates.

Zone R3 (Relatively Safe Zone). The southernmost 270,000 ha (45.8% of district) constitute Zone R3, where groundwater remains deep (mean >5 m) and fresh (mean TDS 2.1 g/L), soils are non-saline or weakly saline (ECe < 4 dS/m), and vegetation trends are stable or increasing. However, "safe" is a relative term: even in Zone R3, groundwater depth decreased by 0.8 m between 2000 and 2024, indicating that salinization risk is expanding southward. The priority is maintenance monitoring: continue annual satellite-based assessment of NDVI and salinity indices, with targeted field sampling every 3-5 years to detect any incipient degradation.

Table 8: Characteristics of ecological risk zones in Karauzyak district

Parameter	Zone R1 (High)	Zone R2 (Moderate)	Zone R3 (Relatively Safe)
Area (ha)	84,600	235,000	270,000
Proportion (%)	14.3	39.9	45.8
Groundwater depth (m)	1.4 ± 0.6	3.1 ± 0.9	5.3 ± 1.2
Groundwater TDS (g/L)	6.2 ± 1.3	3.9 ± 0.8	2.1 ± 0.5
Soil ECe (dS/m)	12.8 ± 3.1	5.9 ± 1.4	2.3 ± 0.9
NDVI trend (Δ/year)	-0.032 ± 0.008	-0.014 ± 0.006	-0.002 ± 0.004
% irrigated cropland	12%	58%	30%
Productivity trend	Rapidly declining	Slowly declining	Stable

The comparison between Karauzyak and Chimbay districts (Table 9) reveals systematically worse conditions in Karauzyak across all indicators, with the magnitude of difference statistically significant for most parameters ($p < 0.05$). Karauzyak has 13% higher total salt-affected area (73% vs. 65% of district), 34% higher proportion of strongly/very strongly saline soils (19% vs. 14%), and 21% shallower groundwater (2.8 m vs. 3.4 m mean depth). The rate of degradation also differs: salinization expanded at 0.32 percentage points per year in Karauzyak vs. 0.28 percentage points per year in Chimbay, and groundwater rose at 5.8 cm/year vs. 4.7 cm/year.

These differences are plausibly attributable to the infrastructure and management factors identified in Table 5. Karauzyak's lower canal lining proportion (15% vs. 38%) means greater seepage to groundwater, directly contributing to water table rise. Its lower drainage density (0.31 vs. 0.62 km/km²) means less capacity to remove excess water from the root zone, perpetuating waterlogged conditions that accelerate salinization. Critically, the absence of a systematic monitoring system in Karauzyak—compared to the GIZ-supported system in Chimbay—has allowed degradation to proceed without detection or response. Farmers and water managers in Karauzyak, lacking the salinity maps and zone-specific recommendations available to their counterparts in Chimbay, continue to apply uniform irrigation schedules that overwater some fields (worsening waterlogging) and underwater others (increasing stress).

Table 9: Comparative indicators: Karauzyak vs. Chimbay districts (2024 values)

Indicator	Karauzyak	Chimbay	Difference (%)	Statistical significance
Salt-affected area (% of district)	73.0%	67.3%	+8.5%	$p < 0.01$
Severe salinity (ECe >8 dS/m, % of district)	18.9%	14.1%	+34%	$p < 0.001$
Mean groundwater depth (m)	2.8 ± 0.9	3.4 ± 1.0	-21%	$p < 0.001$
Groundwater rise rate (cm/year, 2000-2024)	5.8	4.7	+23%	$p < 0.05$
Mean NDVI (cropland, GS)	0.29 ± 0.07	0.33 ± 0.08	-12%	$p < 0.01$
NDVI trend (Δ/year)	-0.014	-0.010	-40%	$p < 0.05$

Conclusions

This study provides the first comprehensive geospatial assessment of land degradation dynamics in Karauzyak district, northern Karakalpakstan, and establishes a replicable monitoring framework that can be operationalized with limited resources. The key conclusions are:

Land degradation in Karauzyak district is widespread (73% of district salt-affected) and accelerating, with severely saline lands increasing by 36% over 24 years. Groundwater has shallowed by 1.4 m (mean depth now 2.8 m) and increased in salinity by 55% (mean TDS now 4.8 g/L). Accelerated degradation since 2010 coincides with reduced Amu Darya flow and inadequate infrastructure maintenance.

Three ecological risk zones were delineated: High Risk Zone R1 (14.3% of district), where conventional agriculture is no longer feasible; Moderate Risk Zone R2 (39.9%), requiring preventive management; and Relatively Safe Zone R3 (45.8%), requiring maintenance monitoring. For each zone, specific management priorities are proposed.

Comparative analysis with Chimbay district—which received external investment in monitoring and infrastructure—reveals systematically worse conditions in Karauzyak, with 13% higher salinity extent, 21% shallower groundwater, and 40% steeper vegetation decline. The difference appears driven by infrastructure (lower canal lining and drainage density) and institutional (absence of systematic monitoring) factors rather than intrinsic biophysical differences.

A low-cost satellite-based monitoring system can be implemented in Karauzyak for $25,000-35,000 in first-year costs and $10,000-15,000 annually thereafter—modest relative to the value of agricultural production at risk. This system would provide early warning of degradation hotspots, enable targeting of interventions, and create accountability for management outcomes.

The methodology developed for Karauzyak is transferable to other northern districts of Karakalpakstan (Moynaq, Taxtako'pir, Kungrad) that currently lack monitoring capacity. Regional scaling would require coordination across districts and investment in training at the Karakalpakstan Ministry of Agriculture level.

The Aral Sea crisis is often framed as an irreversible catastrophe, but the findings of this study suggest a more nuanced interpretation: while some lands

(Zone R1) are indeed beyond conventional agricultural recovery, other lands (Zones R2 and R3) can be maintained or even improved through better management informed by monitoring. The cost of inaction—continued degradation of 73% of the district—will be borne by the rural population of Karauzyak through declining yields, rising production costs, and eventual loss of agricultural livelihoods. The cost of action—implementing the monitoring framework proposed here and acting on its recommendations—is modest by comparison. The question is not whether monitoring is technically feasible, but whether the political will and institutional capacity can be mobilized to sustain it.

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