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REMOTE SENSING-BASED EVALUATION OF LAND DEGRADATION AND MOISTURE VARIABILITY IN POST-NUCLEAR LANDSCAPES OF KAZAKHSTAN

Land degradation and ecosystem imbalance remain major environmental challenges in Kazakhstan, particularly in post-technogenic and radiation-affected territories. The Semipalatinsk Nuclear Test Site represents a unique area for studying long-term landscape transformation and recovery.

This research aims to evaluate land degradation and surface moisture variability between 2019 and 2025 using Sentinel-2 remote sensing data. The methodology integrates the calculation of key spectral indices – SWIR, NDWI, NDVI, and MSI – to assess vegetation dynamics, moisture content, and surface dryness.

Results indicate a noticeable increase in NDVI and NDWI and a decrease in MSI and SWIR, confirming the improvement of soil moisture and vegetation recovery, along with a reduction in aridity. The area of moist and vegetated lands expanded by approximately 20-25 %, demonstrating active natural renaturation processes.

The study highlights the effectiveness of Sentinel-2 multispectral monitoring for ecological rehabilitation assessment in post-technogenic regions of Kazakhstan. The findings contribute to sustainable land management and environmental monitoring in arid landscapes.

Keywords: remote sensing, land degradation, soil moisture, NDVI index, Semipalatinsk Test Site.

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Қашықтықтан зондтау негізінде Қазақстанның ядролық қарудан кейінгі ландшафттарындағы жердің тозуын және ылғалдылықтың өзгергіштігін бағалау

Қазақстанда жердің тозуы мен экожүйе тепе-теңдігінің бұзылуы – әсіресе техногендік және радиациялық әсерге ұшыраған аумақтарда – маңызды экологиялық мәселелердің бірі болып қала береді. Семей ядролық сынақ полигоны ландшафттардың ұзақ мерзімді трансформациясы мен қалпына келуін зерттеуге арналған бірегей аймақ болып табылады.

Бұл зерттеу 2019–2025 жылдар аралығындағы жердің тозу динамикасын және жер беті ылғалдылығының өзгерісін Sentinel-2 спутниктік деректерінің негізінде бағалауға бағытталған. Әдістемеде өсімдік жамылғысының өзгерісін, ылғал мөлшерін және жер бетінің құрғау деңгейін талдау үшін негізгі спектралдық индекстер – SWIR, NDWI, NDVI және MSI – есептеу қарастырылған.

Нәтижелер NDVI және NDWI көрсеткіштерінің айтарлықтай артқанын, ал MSI мен SWIR мәндерінің төмендегенін көрсетті. Бұл топырақ ылғалдылығы мен өсімдіктердің қалпына келуінің жақсарғанын және құрғақшылық деңгейінің азайғанын дәлелдейді. Ылғалды және өсімдік жамылғысы бар жерлердің аумағы шамамен 20–25 %-ға ұлғайып, табиғи ренатурация (қалпына келу) үдерістерінің белсенді жүргенін көрсетті.

Зерттеу Sentinel-2 мультиспектралдық мониторингінің Қазақстанның техногендік әсерден кейінгі өңірлерінде экологиялық қалпына келу деңгейін бағалаудағы тиімділігін көрсетті. Алын-

ған нәтижелер құрғақ аймақтардағы жер ресурстарын ұтымды басқару мен экологиялық мониторингті жетілдіруге үлес қосады.

Түйін сөздер: қашықтықтан зондтау, жердің деградациясы, ылғалдылық, NDVI индексі, Семей полигоны.

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Оценка деградации земель и изменчивости влажности в постъядерных ландшафтах Казахстана на основе дистанционного зондирования

Деградация земель и нарушение экологического равновесия остаются одними из ключевых экологических проблем Казахстана, особенно на посттехногенных и радиационно загрязнённых территориях. Семипалатинский ядерный испытательный полигон представляет собой уникальную природную лабораторию для изучения долгосрочных процессов трансформации и восстановления ландшафтов.

Цель данного исследования – оценить деградацию земель и вариации поверхностной влажности за период с 2019 по 2025 год на основе данных дистанционного зондирования Sentinel-2. Методика включает расчёт основных спектральных индексов – SWIR, NDWI, NDVI и MSI, позволяющих оценить динамику растительного покрова, содержание влаги и степень сухости поверхности.

Результаты показали заметное увеличение значений NDVI и NDWI, а также снижение MSI и SWIR, что свидетельствует о повышении влажности почвы, восстановлении растительности и сокращении аридности. Площадь увлажнённых и покрытых растительностью земель увеличилась примерно на 20–25 %, что указывает на активное протекание процессов естественной ренатурации.

Исследование подтвердило высокую эффективность мультиспектрального мониторинга Sentinel-2 для оценки экологической реабилитации посттехногенных территорий Казахстана. Полученные результаты вносят вклад в развитие системы устойчивого землепользования и экологического мониторинга в аридных ландшафтах.

Ключевые слова: дистанционное зондирование, деградация земель, влажность почв, индекс NDVI, Семипалатинский полигон.

Introduction

The problem of land degradation is one of the most acute environmental and socio-economic threats of our time, especially for territories that have been subjected to intense anthropogenic impact. As a result of industrial, military, and agricultural activities during the 20th century, a significant part of the earth's ecosystems underwent irreversible changes, manifested in the destruction of soil cover, reduced bio-productivity, loss of biodiversity, and disruption of the hydrological balance (Бобровский М.В., Нечаев В.П., 2022).

A special place among such territories is occupied by post-technological landscapes, including areas of former industrial zones, landfills, quarries and nuclear test sites (Есиркеев А.М., Алимбекова Г.Ж., 2021). They are characterized by difficult environmental conditions caused by prolonged exposure to radiation, chemical pollution and physical destruction of the surface.

One of the most striking examples of such territories is the Semipalatinsk Nuclear Test Site (NSNR), which operated in Kazakhstan from 1949 to 1989. During this period, more than 450 nuclear explosions were carried out here, which led to significant changes in the geomorphological structure, soil composition and vegetation cover. Despite the cessation of testing and the subsequent declaration of the landfill as a restricted access zone, the processes of ecosystem restoration here remain extremely slow. Against the background of the general aridity of the region, there is a high spatial mosaic of the state of soils and vegetation, which complicates the assessment of the degree of degradation and the dynamics of restoration (Горшков И.А., 2023).

Post-technological territories, especially such as the NSNR, are characterized by a combination of

natural and induced degradation factors. On the one hand, the arid climate, low precipitation and poor vegetation development contribute to erosion processes and deflation. On the other hand, man-made impacts – soil compaction, radiation pollution, and disruption of the hydrological regime – enhance these processes, creating stable pockets of degradation. As a result, specific post-nuclear landscapes are formed, which are characterized by a combination of dry, burnt-out areas, secondary salt marshes, fragmentary vegetation and local zones of temporary humidification.

Modern approaches to the study of such territories require a comprehensive assessment of degradation processes and ecosystem restoration using objective and spatially continuous data. Traditional field monitoring methods are limited here due to the large areas, inaccessibility and potential radiation risk (Шевченко И.С., 2021). Therefore, remote sensing technologies are becoming the main analysis tool for assessing the dynamics of vegetation, humidity, and soil conditions based on the spectral characteristics of the surface.

The use of satellite data, such as Sentinel-2, provides extensive opportunities for quantifying the state of degraded ecosystems. By calculating spectral indices – NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), MSI (Moisture Stress Index) and SWIR channel analysis – it is possible to detect changes in vegetation structure, the level of moisture availability and the intensity of soil degradation. These indicators allow not only to determine the current state of the territory, but also to track the dynamics of ecosystem restoration over time.

In Kazakhstan, where most of the lands are subject to aridization, wind and water erosion, monitoring of land degradation and the processes of their natural restoration is becoming particularly relevant (Асылбекова А., Мукалиев Ж., Азимханов Б., 2021). Using the example of the Semipalatinsk test site, such studies make it possible not only to determine the degree of anthropogenic impact and current environmental risks, but also to assess the effectiveness of the renaturalization processes taking place over the past decades (Bai, Z.G., Dent, D.L., 2009).

The integration of modern remote sensing data with geoinformation analysis methods creates the basis for a comprehensive assessment of the state of post-technological ecosystems and the development of strategies for their ecological restoration.

The current state of the landfill can be described as a stage of slow but steady natural recovery, in which ecosystems show signs of adaptation and self-regulation in a post-nuclear landscape (Carlsen, T.M., Groves, R.A., et al., 2021). This makes the region a unique model territory for studying the long-term processes of ecological rehabilitation of degraded lands in the arid climate of Central Asia.

Materials and methods

Study area. The Semipalatinsk Test Site is located in the north-east of the Republic of Kazakhstan, within the East Kazakhstan, Pavlodar and partially Karaganda regions. The geographical coordinates of the central part of the test site are approximately 50° 15’ N and 78°40’ E. The total area of the territory historically used for nuclear testing exceeds 18,000 km2, and together with the adjacent zone of influence is estimated at about 19-20 thousand km2.

The terrain of the polygon is predominantly flat and undulating, with elements of weak uplifts and depressions characteristic of the eastern edge of the Central Kazakhstan plateau. The absolute heights range from 250 to 500 m, occasionally reaching 600 m in the eastern part. The territory is divided by a network of temporary watercourses and small hollows, through which meltwater and rainwater flow (Сагидуллина Д.Б., Омаров Р.Е., 2023). The main rivers of the region – Shagan, Ashchysu, Kokental – are temporary and seasonal in nature, which causes a high sensitivity of the soil and vegetation cover to moisture availability.

The climate of the area is sharply continental and arid. The average annual air temperature is about +3...+4 °C, the average temperature in January is -16 °C, in July – +21...+24 °C. Annual precipitation does not exceed 250 – 300 mm, of which about 60% falls in spring and early summer. Summers are hot and arid, winters are long with stable snow cover. Winds prevail from the northwest and west, contributing to the development of deflationary and erosive processes.

The soil cover is mainly light chestnut, chestnut and brackish soils, with salt marshes and sandy loam rocks found in places. Vegetation is desert-steppe, with a predominance of xerophytic and grass-wormwood communities.

Atmospheric correction and radiometric consistency were verified and, where necessary, slightly adjusted on the basis of reference reflectance and visual inspection.

- 116 atmospheric (terrestrial and aerial);

- 340 underground tunnels and boreholes.

Large-scale activity led to powerful radioactive emissions, mechanical destruction of the soil and vegetation cover and the formation of a whole complex of post-nuclear landscapes – craters, subsidence, burnt-out areas, radiation-contaminated hollows and man-made landforms.

The areas within the Experimental Field, Balapan, Degelen and Sary-Uzen districts, where the main test facilities were concentrated, were particularly affected. Elevated levels of gamma radiation, residual isotopes of cesium, strontium and plutonium in the soils are still recorded at these sites (Мукалиев Ж.К., 2020).

The consequences of nuclear tests are long-term in nature – soil degradation, violation of the water regime, decrease in vegetation productivity and secondary salinization. Even three decades after the closure of the landfill, the environmental consequences remain significant and manifest themselves in a decrease in biological activity, erosion processes and fragmented ecosystems.

After the official closure of the Semipalatinsk landfill in 1991, the territory was declared a zone of restricted nature use, which contributed to the natural processes of renaturalization. In the absence of economic stress, there is a gradual restoration of the grass cover and the soil humus horizon.

Cereal-wormwood communities began to develop in areas with low levels of radiation pollution, and the processes of natural overgrowth of craters and accumulation of organic matter intensified. Areas with high humidity are formed along the valleys of temporary watercourses, where species characteristic of meadow-steppe phytocenoses are actively growing (Зайцева Н.Н., Морозов Е.А., 2020).

Nevertheless, the recovery is uneven. In areas with high levels of radionuclide contamination and mechanical disturbance of the soil profile, natural processes are slowed down or completely suppressed. A number of sites remain unproductive and degraded, which is reflected in low NDVI and NDWI values according to satellite monitoring data.

This study utilized multi-temporal satellite data from the Sentinel-2 Level-2A mission, provided by the European Space Agency (ESA) under the Copernicus Programme. Two cloud-free images covering the central and adjacent parts of the Semipalatinsk Nuclear Test Site (SNTS) were selected for analysis, corresponding to May 11, 2019 and May 29, 2025 (European Space Agency (ESA), 2024).

Level-2A products include bottom-of-atmosphere reflectance, already corrected for atmospheric and radiometric effects using the Sen2Cor processor, ensuring high accuracy of spectral values across visible, near-infrared (NIR), and short-wave infrared (SWIR) bands.

The Sentinel-2 system provides a spatial resolution of 10-20 m, which is suitable for landscape-level monitoring of soil, vegetation, and moisture dynamics in heterogeneous arid regions such as eastern Kazakhstan (European Space Agency, 2024).

All satellite scenes were preprocessed in QGIS 3.34 and ArcGIS Pro 3.2.

The threshold values used for the classification of NDVI, NDWI and MSI (Table 2) were defined based on a combination of published recommendations and empirical calibration for the conditions of the Semipalatinsk Nuclear Test Site. The lower and upper NDVI bounds for degraded, transitional and dense vegetation were chosen in accordance with earlier studies on steppe and arid ecosystems of Kazakhstan, while NDWI and MSI thresholds were refined using visual interpretation of Sentinel-2 composites and previously published descriptions of soils and vegetation for the region.

For each index and each year, mean, minimum, maximum and standard deviation values were calculated for the entire test site and for the three physiographic zones (northern, central, southern). In addition, difference maps (2025–2019) and histograms of index distributions were analysed to assess the magnitude and spatial structure of changes. In this study we focused on descriptive statistics and visual comparison; a formal test of statistical significance is planned for future work.

The following steps were performed:

• Radiometric consistency and atmospheric conditions of Sentinel-2 Level-2A bottom-of-atmosphere reflectance products were visually checked for both dates to ensure their suitability for multi-temporal comparison.

• Cloud and shadow masking was implemented using the Scene Classification Layer (SCL) provided within Sentinel-2 data. Pixels classified as clouds, cirrus, or shadows (classes 8, 9, 10, 3) were excluded from analysis.

• Subsetting of the study area was performed according to the official polygon boundaries of the Semipalatinsk Test Site.

• Radiometric values were rescaled to the range 0–1 for further index calculations.

Calculation of Spectral Indices

To quantify vegetation activity, soil moisture, and surface dryness, four key spectral indices were derived from Sentinel-2 reflectance data (Table 1).

Table 1 – Description of spectral indices and their environmental interpretation

Index	Formula	Bands (Sentinel-2)	Environmental meaning
SWIR composite	RGB = (B12, B8A, B4)	2190 nm, 865 nm, 665 nm	False-color infrared visualization highlighting dry and moist areas
NDWI	(B3 − B8) / (B3 + B8)	560 nm, 842 nm	Indicates surface and vegetation moisture; higher values = higher water content
NDVI	(B8 − B4) / (B8 + B4)	842 nm, 665 nm	Measures vegetation vigor and biomass; higher values = denser vegetation
MSI	B11 / B8	1610 nm, 842 nm	Moisture Stress Index; higher values = drier vegetation and soils

All indices were computed using raster-based map algebra in QGIS Raster Calculator and ArcGIS scripts, and subsequently normalized to eliminate radiometric differences between dates. The resulting raster layers were resampled to a common 10 m resolution and clipped to the study area boundaries.

Table 2 – Classification of spectral index values and their environmental interpretation

Index	Value range	Environmental interpretation	Surface condition
NDVI (Normalized Difference Vegetation Index)	0.00 – 0.33	Bare soil, degraded land, minimal vegetation	Low biomass, high degradation
	0.33 – 0.50	Sparse or moderate vegetation cover	Transitional zone
	> 0.50	Dense and healthy vegetation	High biomass, active photosynthesis
NDWI (Normalized Difference Water Index)	< 0.00	Dry and arid surfaces	Lack of surface moisture
	0.00 – 0.30	Moderately moist soils or sparse vegetation	Moderate humidity
	> 0.30	Wet soils or open water bodies	High surface moisture or inundation
MSI (Moisture Stress Index)	< 0.80	Low stress; sufficient moisture availability	Favorable conditions for vegetation
	0.80 – 1.20	Moderate moisture stress	Transitional soil moisture
	> 1.20	High dryness or stressed vegetation	Drought or degraded land

The threshold values used for the classification of NDVI, NDWI and MSI presented in Table 2 were defined based on a combination of published recommendations and empirical calibration for the conditions of the Semipalatinsk Nuclear Test Site. The lower and upper NDVI bounds for degraded, transitional and dense vegetation were chosen in accordance with earlier studies on steppe and arid ecosystems of Kazakhstan (Бобровский М.В., Нечаев В.П., 2022; Горшков И.А., 2023; Зайцева Н.Н., Морозов Е.А., 2020), while NDWI and MSI thresholds were refined using visual interpretation of Sentinel-2 composites and previously published descriptions of soils, moisture regime and vegetation in the test site area (Сагидуллина Д.Б., Омаров Р.Е., 2023; Асылбекова А., Мукалиев Ж., Азимханов Б., 2021).

Each raster was statistically summarised to calculate mean, minimum, maximum and standard deviation values for both years and for the three physiographic zones (northern, central, southern). Difference maps (2025 − 2019) and histograms of index distributions were generated to visualise the spatial pattern and magnitude of changes in vegetation greenness, surface moisture and soil dryness. In this study we focused on descriptive statistics and visual comparison of index dynamics; a more detailed formal assessment of statistical significance is planned for future work.

Spatial differentiation was conducted by dividing the study area into three physiographic zones – northern, central and southern – reflecting the main geomorphological and hydro-ecological variations within the polygon. The combined analysis of the four indices provided a comprehensive evaluation of the eco-hydrological changes within the Semipalatinsk Test Site over the six-year period. A decrease in MSI and SWIR brightness,

coupled with an increase in NDWI and NDVI, was interpreted as a sign of improved soil moisture and vegetation recovery (Pettorelli et al., 2005; Li et al., 2020). Statistical summaries and thematic maps were integrated in a GIS environment to assess the extent of rehabilitation versus degradation zones, forming the basis for further discussion and conclusions.

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Statistical summaries and thematic maps were integrated in a GIS environment to assess the extent of rehabilitation versus degradation zones, forming the basis for further discussion and conclusions.

Results

Multi-temporal index maps (2019 – 2025). The generated maps of SWIR, NDWI, NDVI, and MSI for 2019 and 2025 (Figures 5 – 8) clearly demonstrate notable spatial and temporal changes in the surface characteristics of the Semipalatinsk Nuclear Test Site.

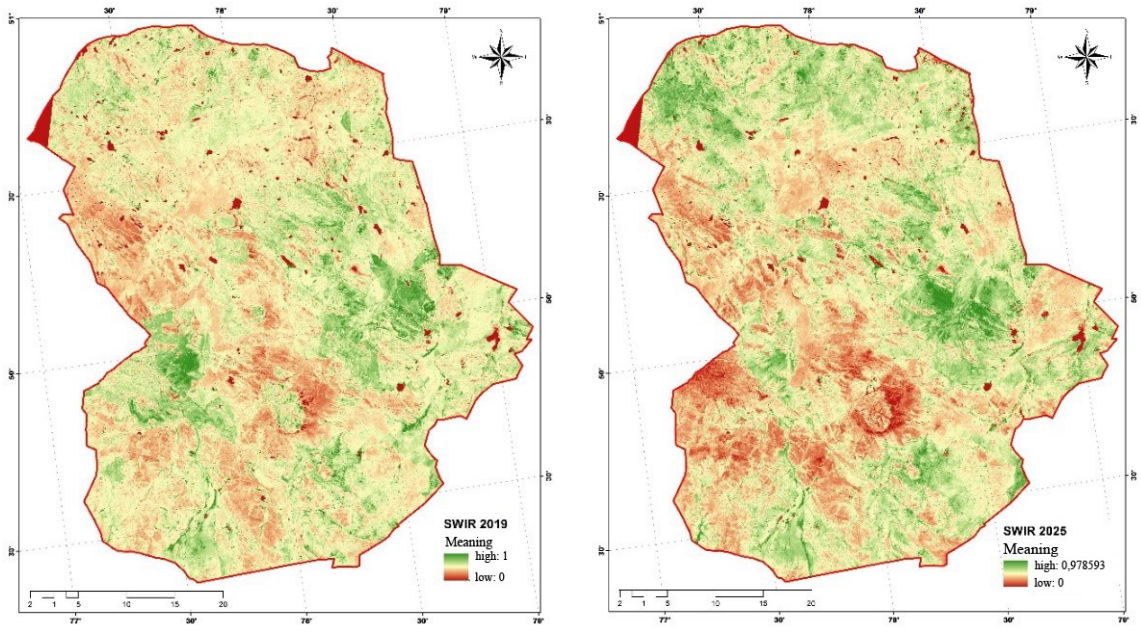

Figure 1 – SWIR (source: own study)

Overall, approximately 65 % of the territory exhibited improvement in vegetation and moisture indices, around 25 % remained relatively stable and about 10 % still shows clear signs of degradation.

The Moisture Stress Index (MSI) also shows a downward trend, suggesting a general reduction of drought-related stress in vegetation.

The results show a consistent improvement in eco-hydrological indicators between 2019 and 2025. The most significant positive shifts are observed in NDVI (+0.16) and NDWI (+0.15), while the decline in MSI (−0.18) further confirms the trend toward enhanced soil moisture and vegetation health (Li J., et al., 2020).

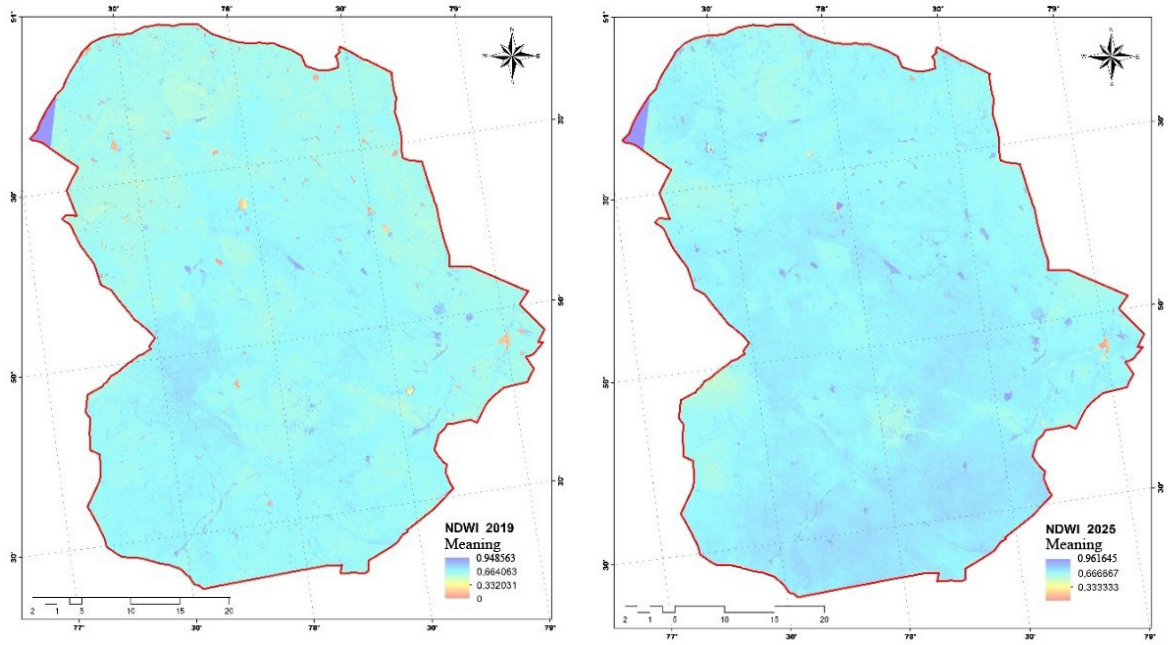

Figure 2 – NDWI (source: own study)

Table 3 – Statistical summary of mean index values

Spectral Index	Mean (2019)	Mean (2025)	Δ Change (2025 − 2019)	Environmental trend
SWIR (12–8A–4)	0.46	0.39	−0.07	Decrease of surface dryness
NDWI	0.12	0.27	+0.15	Increase in soil and vegetation moisture
NDVI	0.32	0.48	+0.16	Expansion of vegetated areas
MSI	1.23	1.05	−0.18	Lower vegetation water stress

Spatial distribution of landscape changes. Spatial differentiation analysis revealed distinct regional patterns (Figure 3):

- Northern zone – notable increase in NDVI and NDWI (up to +0.2 – 0.3), associated with vegetation recovery in depressions and along seasonal watercourses.

- Central zone – heterogeneous pattern with dominant moderate increases in NDVI and NDWI and a visible reduction of high-MSI areas; this zone represents the most active phase of natural renaturation.

- Southern zone – minor positive trends with remaining arid patches (high SWIR and MSI), indicating slower recovery due to poor soil structure and limited hydrological recharge.

Overall, approximately 65 % of the territory exhibited improvement in vegetation and moisture indices, around 25 % remained relatively stable, and about 10 % still shows clear signs of degradation.

The use of Sentinel-2 (L2A) data and spectral indices (SWIR, NDVI, NDWI, MSI) for the period 2019-2025 showed a clear trend towards an increase in humidity and bio-productivity in most of the landfill area (Gorelick, N., et al., 2017). Positive changes are especially noticeable in the central and northeastern parts, where there is a decrease in the MSI (Moisture Stress Index) and an increase in NDVI and NDWI, indicating a gradual restoration of ecosystems and stabilization of the microclimate.

The combined index analysis suggests that eco-hydrological restoration processes are actively progressing across the Semipalatinsk Test Site.

The decrease in SWIR and MSI reflects the gradual reduction of soil aridity and water stress, while the increase in NDVI and NDWI indicates enhanced vegetation productivity and moisture retention.

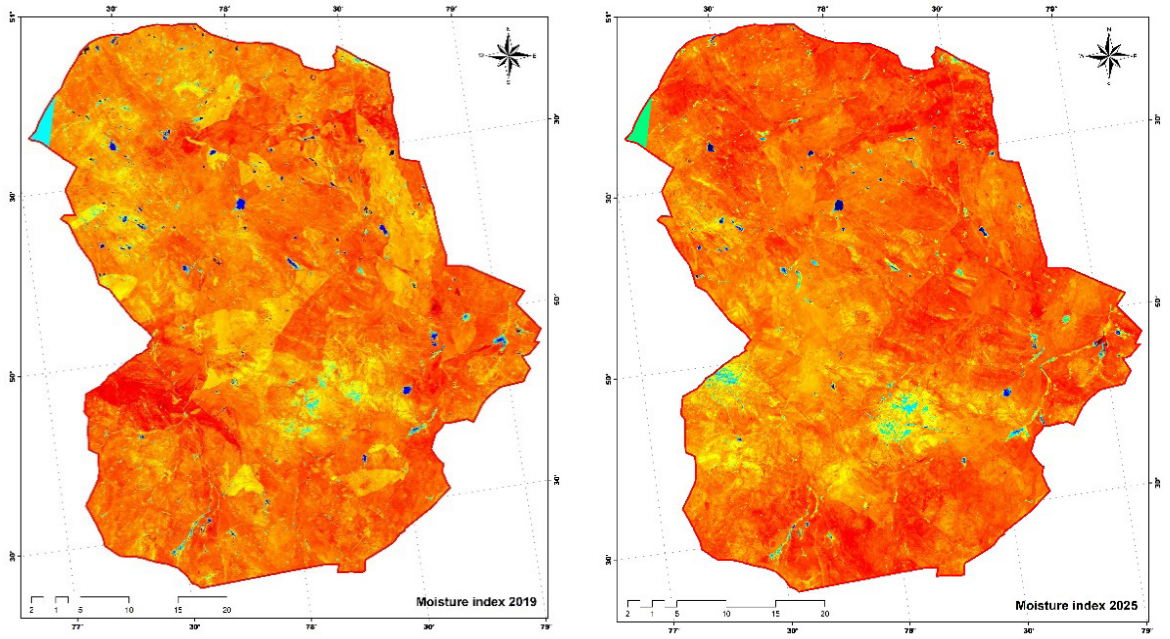

Figure 3 – MSI (source: own study)

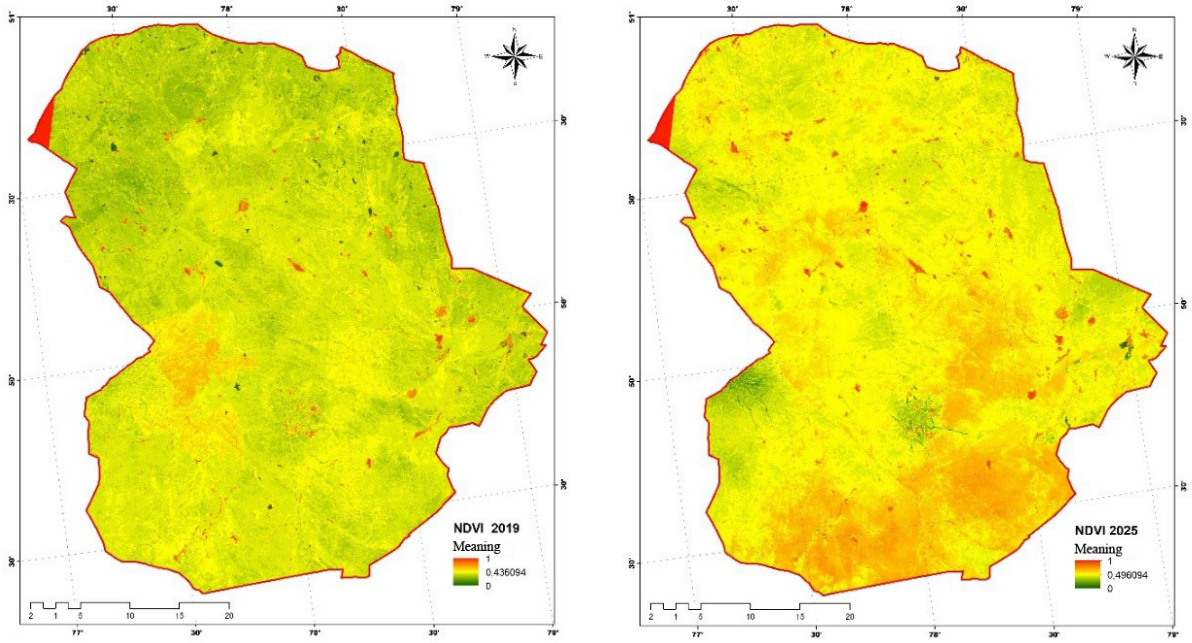

Figure 4 – NDVI (source: own study)

Meteorological observations from regional stations in eastern Kazakhstan and recent climatological assessments indicate a statistically significant increase in mean and maximum air temperatures in the region, while precipitation shows weak but generally positive trends over the last decades (Салников В. и др., 2015; Салников В. и др., 2023; Makhambetova et al., 2024; РГП «Казгидромет», 2024). These tendencies are consistent with the satellite-based results obtained in this study: higher NDWI and NDVI values together with reduced SWIR reflectance and MSI indicate more favourable hydrothermal conditions for vegetation growth and a gradual reduction in drought stress.

Thus, gradual climate moderation appears to enhance natural renaturation processes and contributes to the eco-hydrological stabilization of the Semipalatinsk landscape, while index-based monitoring clearly reflects the close relationship between climate dynamics and the state of the soil and vegetation cover.

These results confirm that the post-nuclear landscape is undergoing slow but steady ecological rehabilitation, particularly within the northern and central physiographic units.

The findings also highlight the potential of using integrated Sentinel-2 spectral indices as effective indicators for monitoring land-degradation reversal and natural recovery in post-technogenic environments.

Discussion

The present study assessed land degradation and moisture dynamics within the Semipalatinsk Nuclear Test Site between 2019 and 2025 using Sentinel-2 Level-2A data and a set of spectral indices (SWIR composites, NDVI, NDWI, MSI). The integrated remote sensing and GIS-based approach provided a spatially explicit characterization of eco-hydrological changes in a large post-nuclear landscape under arid climatic conditions.

The results indicate a consistent improvement of environmental conditions over the six-year period. Mean NDVI and NDWI values increased, while MSI and SWIR reflectance decreased, reflecting enhanced soil moisture, higher vegetation productivity and reduced surface dryness. Quantitatively, the area of moist and vegetated lands expanded, whereas the proportion of strongly arid and degraded surfaces declined, with the most pronounced positive changes observed in the central and northern parts of the test site.

The study confirms that Sentinel-2 multispectral monitoring, combined with index-based classification and GIS analysis, is an effective and cost-efficient tool for tracking ecological rehabilitation in post-technogenic territories of Kazakhstan. The proposed methodology can be applied for regular monitoring of remote and radiation-hazardous areas, informing environmental planning and sustainable land management in arid and semi-arid regions.

Future research should focus on integrating satellite-derived indices with climatic and hydrological data, as well as on exploiting longer time series and machine-learning methods to better predict degradation and recovery trajectories. The inclusion of radar observations (for example, Sentinel-1) would further improve the robustness of soil moisture and vegetation assessments under cloudy conditions and support the development of national systems for environmental monitoring and land-resource protection in Kazakhstan.

The purpose of the study was to assess the processes of land degradation and the dynamics of moisture availability within the Semipalatinsk Nuclear Test Site (NSNR) using Sentinel-2 multitime remote sensing data. To achieve this goal, the spectral indices SWIR, NDWI, NDVI and MSI were used, which made it possible to comprehensively characterize changes in the state of the soil and vegetation cover for the period 2019 – 2025.

The technique used included atmospheric correction of Sentinel-2 Level-2A data, cloud masking, and calculation of spectral indices reflecting the degree of degradation, humidity, and plant restoration. A comparative analysis showed a clear trend towards an improvement in the ecological condition of the territory: an increase in NDVI and NDWI values, a decrease in MSI and SWIR brightness indicate an increase in humidity, bio-productivity and ecosystem stability.

The quantitative assessment showed that the area of moistened and vegetating lands increased by about 20 – 25%, while the proportion of arid and degraded areas decreased by 10 – 15%. These changes indicate a gradual restoration of natural processes and ecosystem stability in the post-nuclear territory. It is noted that the greatest positive transformations are taking place in the central and northeastern zones of the landfill, where active renaturalization and restoration of vegetation cover are observed.

The results obtained confirm that the integration of Sentinel-2 multispectral data and the calculation of key indices (SWIR, NDWI, NDVI, MSI) is an effective and economically justified tool for monitoring environmental rehabilitation of post-technological territories of Kazakhstan.

The practical significance of the work lies in the fact that the developed methodology can be used for:

- regular monitoring of land degradation and vegetation restoration in remote and radiation-hazardous areas;
- environmental planning and environmental management aimed at land restoration in arid zones of Kazakhstan;
- building a national remote environmental monitoring system based on open satellite data.

The prospects for further research are related to the integration of satellite and climate data (precipi-

tation, temperature, humidity), as well as the use of machine learning and Sentinel-2 time series analysis to predict the dynamics of degradation processes and assess the rate of ecosystem restoration.

Thus, the work carried out not only confirms the effectiveness of remote sensing methods for studying post-nuclear landscapes, but also makes a significant contribution to the development of geoinformation monitoring of the environmental sustainability of the territories of Kazakhstan.

The conducted research has contributed to the development of scientific ideas about the mechanisms of restoration of post-nuclear landscapes and the improvement of approaches to their remote assessment. The integration of the SWIR, NDWI, NDVI, and MSI indexes has made it possible to create a reproducible methodology for eco-hydrological monitoring of disturbed territories, which can be used in other arid and semi-arid regions of Central Asia, where field research is limited.

A comparison with similar studies conducted in radioactive contamination zones such as Fukushima (Japan) and the Nevada Test Site (USA) shows similar recovery trends – gradual vegetation growth and increased soil moisture. However, unlike these regions, the landscapes of Kazakhstan are characterized by a more pronounced climatic dependence and spatial heterogeneity of restoration, which requires long-term and detailed monitoring.

A number of limitations of the study should be noted, related to seasonal variability, sensor differences, and insufficient validation by field observations. In the future, it is advisable to integrate satellite and climate data (precipitation, temperature, humidity) and use machine learning and Sentinel-2 time series analysis methods to predict the dynamics of degradation and the rate of ecosystem restoration.

The additional inclusion of Sentinel-1 radar survey data will improve the accuracy of soil moisture and vegetation assessment in cloudy conditions.

Thus, the conducted research has shown that remote sensing technologies and geoinformation analysis are indispensable tools for long-term environmental monitoring of territories exposed to anthropogenic and radiation effects.

The experience gained from studying the Semipalatinsk test site can serve as a model for building national environmental monitoring systems, as well as for improving the policy of sustainable environmental management and protection of Kazakhstan's land resources.

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Conflict of interest

There is no conflict of interest.

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