

Article

Assessment of Landscape Resilience to Anthropogenic Impact in the Western Kazakhstan Region

Aigul Tokbergenova ¹, Aizhan Ryskeldiyeva ¹, Aizhan Mussagaliyeva ^{1,*} , Irina Skorintseva ², Damira Kaliyeva ¹, Alibek Beimbetov ¹, Ulan Mukhtarov ¹ and Bekzat Bilalov ¹

¹ Department of Geography, Land Management and Cadastre, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan; damira.kaliyeva@kaznu.edu.kz (D.K.); aliko9292@mail.ru (A.B.); bilalov.bekzat@mail.ru (B.B.)

² Institute of Geography and Water Security of the Republic of Kazakhstan, Almaty 050000, Kazakhstan

* Correspondence: aizhan.mussagaliyeva@kaznu.edu.kz

Abstract

This paper presents a comprehensive methodology for assessing the resilience of landscapes to human impact in western Kazakhstan. The approach developed is based on integrating remote sensing data (MODIS, SMAP, NDVI and NDSI), the results of field surveys, and multi-criteria analysis methods in a GIS environment. The assessment covered over 50 landscape types and subtypes using ten key indicators reflecting climatic, geomorphological, soil, hydrological, and biotic characteristics. These indicators were normalised, aggregated and summarised to create an integral index of landscape resilience, which allowed four resilience classes to be identified, ranging from highly vulnerable to relatively resilient. The spatial analysis revealed that over 60% of the region's territory is classified as high-vulnerability, predominantly within semi-desert and desert zones, which are vulnerable to climatic risks, degradation of vegetation cover and human activity. Verification of the results based on remote monitoring data for the period 2000–2024 and field observations confirmed the reliability of the developed methodology. The results obtained allow the identification of areas prioritised for environmental monitoring, restoration and sustainable land use in arid climate conditions. A plan of measures for regulation and restoration of ecosystems and spatial planning tools are proposed. The obtained data can be used for the development of regional environmental policy and sustainable land use strategies.

Keywords: landscape resilience; anthropogenic impact; remote sensing; Western Kazakhstan region; ecological vulnerability; sustainable land use



Academic Editor: Richard Ross Shaker

Received: 26 July 2025

Revised: 13 September 2025

Accepted: 18 September 2025

Published: 24 September 2025

Citation: Tokbergenova, A.; Ryskeldiyeva, A.; Mussagaliyeva, A.; Skorintseva, I.; Kaliyeva, D.; Beimbetov, A.; Mukhtarov, U.; Bilalov, B. Assessment of Landscape Resilience to Anthropogenic Impact in the Western Kazakhstan Region. *Sustainability* **2025**, *17*, 8584. <https://doi.org/10.3390/su17198584>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The scientific debate on the nature of landscape resilience began in the 1970s and remains relevant to this day. It is far from over, particularly in regions where natural ecosystems undergo intensive change due to agriculture, industry, and climate change [1]. There are significant differences in approaches to interpreting the concept of “sustainability”. Ecosystem stability is defined as its ability to preserve its structure and functions under the influence of external factors [2]. It can also be considered as a combination of normal functioning, the ability to recover, and irreversible transformations [3]. Another interpretation highlights the return of natural systems to a normal state after the removal of anthropogenic pressure [4]. Two types of stability are distinguished: resistance to impact and restoration of functioning [5]. Sustainability is also associated with homeostasis, defined as the capacity

of a system to revert to its original state [6]. At the same time, it is interpreted as the ability of ecosystems to adapt to changes and move to a new equilibrium [7], while another definition emphasizes the preservation of the structure and functions of geosystems within one invariant [8]. In the field of Western ecological science, sustainability is increasingly being interpreted as the capacity of the landscape to provide ecosystem services in a stable manner, thereby ensuring the maintenance and enhancement of human well-being [9].

Particular attention is drawn to studies on sustainability in arid and semi-desert zones, where the combination of limited water resources and climatic risks increases the vulnerability of natural systems [10–13]. In Kazakhstan, similar research has been carried out mainly in specific areas, particularly in the assessment of the resilience of steppe and desert ecosystems [14–17]. However, comprehensive studies that integrate data on climate, topography, soils, and anthropogenic pressures have not yet been conducted for the territory of the Western region. As Geldiyeva notes, in regions of oil production, processing, and transportation, priority should be given to defining sustainability assessment criteria for natural-technogenic systems and mapping territorial structures in accordance with zonal patterns. This underscores the need for an integrated approach that combines natural feature analysis with evaluations of anthropogenic impact to inform effective natural resource management [18].

Assessing landscape stability is challenging due to the absence of a direct measurement method or a universal indicator. Consequently, most researchers adopt integrated approaches based on point- or index-based systems [19]. These methods account for the complex interactions between natural and anthropogenic factors influencing landscape resilience.

In Western Kazakhstan, key vulnerability factors include climatic aridity, pronounced temperature variability, terrain characteristics, and the degradation of soil and vegetation cover resulting from industrial and economic activities. This combination generates spatial heterogeneity in landscape stability, delineating zones with varying capacities for natural regeneration and ecological resilience [20].

In this study, special attention is paid to determining the spatial differentiation of the resistance of landscapes in the West Kazakhstan region to anthropogenic impact, and to identifying the natural and anthropogenic factors that determine this resistance most effectively.

Based on the identified trends, it is reasonable to assume that the semi-desert and desert landscapes of the region have the lowest potential stability when subjected to the combined effects of natural factors (such as an arid climate and high temperature fluctuations) and anthropogenic factors.

The study aimed to comprehensively assess and map the sustainability of landscapes in West Kazakhstan based on an integral indicator incorporating climatic, morphometric, soil, and biotic factors.

The novelty of the study lies in the fact that, for the first time, a spatial assessment of landscape stability was performed for the territory of Western Kazakhstan using a comprehensive set of indicators that integrated remote sensing data and field survey results. This approach enabled the creation of a sustainability map providing an objective ranking of territories according to their vulnerability, which can serve as a basis for the subsequent monitoring of landscapes and the planning of protection and restoration measures. Approval of the technique using a large arid region as an example demonstrated its scientific and practical significance, confirming its potential application in other regions with similar natural conditions.

2. Materials and Methods

2.1. Study Area

The West Kazakhstan region, which includes the Aktobe, Atyrau, West Kazakhstan, and Mangystau regions, covers an area of 736,000 square kilometers, or 27% of Kazakhstan's total territory. It is located between $41^{\circ}21'08''$ to $51^{\circ}43'15''$ N latitude and $46^{\circ}29'22''$ to $64^{\circ}08'57''$ E longitude (Figure 1). Its remoteness from the ocean plays a key role in shaping its arid climate [21].

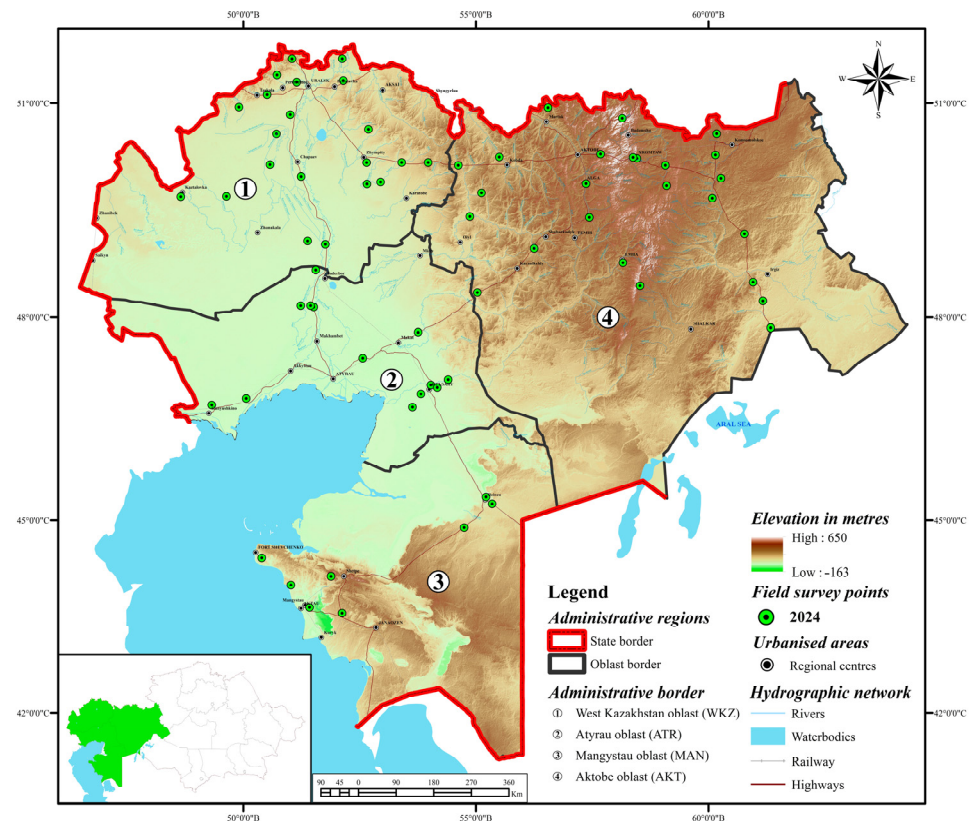


Figure 1. Study Area of the Western Kazakhstan Region. Geographical location and administrative boundaries of the study area. Source: compiled by the authors using ArcGIS Map 10.8.2 and regional base maps.

The region stretches over 1000 km from north to south and more than 1200 km from west to east. Its terrain is primarily flat, with the Mugalzhyry and southern Ural Mountains in the east, and low mountains in the southern part of the Mangystau region. The southwestern part features the Naryn sand massif with Aeolian relief forms. The areas adjacent to the Caspian Sea, the lower left bank of the Ural River, northern Mangystau, southeastern Atyrau, and southern Aktobe are marked by widespread litter deposits. The southern and southeastern parts are elevated plains, including the Ustyurt and Mangyshlak plateaus. Due to the vast area and varied relief, the region experiences diverse climatic conditions that influence its soil and vegetation cover.

Western Kazakhstan lies within the steppe, dry-steppe, semi-desert, and desert zones of the temperate zone, characterized by specific soil and vegetation types. Rising average annual temperatures, extended periods of heat and cold, and a decreasing trend in annual precipitation—from 300 mm in the north to 100 mm in the south—negatively impact soil formation and vegetation. The climatic factor, including precipitation variability over recent decades, plays a key role in the dynamics and development of the region's soil and vegetation cover.

Anthropogenic modifications of soils are widespread throughout the region, with the highest concentration in the northern half and the lowest in the southern half. The northern part has been extensively plowed, and this process has been ongoing dynamically for the past century. Nearly the entire territory, except for areas occupied by settlements and industrial enterprises, is used as pasture.

Over the past 50–70 years, numerous mineral deposits have been explored in the region, with most being extracted through open-pit methods, which leads to the degradation of soil as a natural component. Oil spills, dirt roads, waste, and dumps associated with mining activities contribute to the near-total destruction of the soil cover by disrupting soil structure and introducing toxic substances into the environment.

2.2. Data Sources

The sustainability map was compiled using a range of data sources, including thematic maps, the authors' previously developed map of anthropogenic landscape disturbance [22], satellite imagery (remote sensing), field survey data, and the OpenStreetMap database, which was employed to verify and refine the spatial accuracy of mapped features.

Remote Sensing Data Processing Methods

Remote sensing and ancillary data underwent both preliminary and final processing to ensure consistency, accuracy, and suitability for integration into the final sustainability map (Figure 2). Processing included standard corrections, classification, and alignment with field observations.

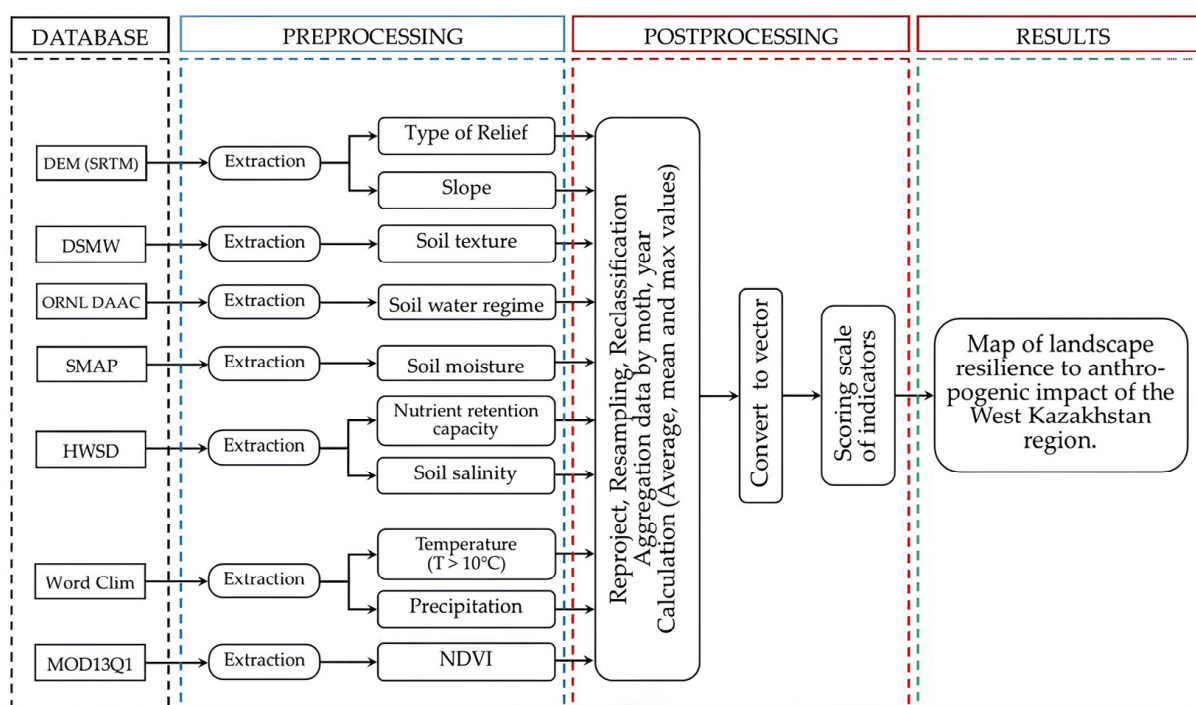


Figure 2. Methodological Workflow for Landscape Resilience Mapping. Processing sequence of geospatial and field data including satellite imagery (MODIS, SMAP), climatic parameters, and land use data.

Natural parameters within the study area were extracted and processed using ArcGIS Pro 3.0.1. Terrain and slope analyses utilized a 30 m resolution SRTM digital elevation model. Other spatial datasets, originally at 250 m resolution and differing coordinate systems, were standardized by resampling and reprojection to a unified spatial reference and resolution. In addition, the Google Earth Engine cloud platform was used to analyze

climate variables (air temperature and precipitation), as well as MODIS and SMAP data, providing efficient processing and visualization of geospatial information. The resulting output data underwent quality control (noise, defects, mosaic quality, and data structure) and post-processing steps, including projection transformation and time interval aggregation. Basic statistical parameters (mean, maximum, and minimum) were derived from the multi-year raster datasets and classified into five classes based on predefined threshold values. Subsequently, the classified rasters were converted to vector format, with attribute data assigned to include class identifiers and corresponding statistical values. In the final stage of the sustainability mapping process, each vector feature was assigned a score from 1 to 5, indicating the degree of landscape resilience to anthropogenic impact in the West Kazakhstan region.

2.3. Method for Calculating the Integral Index

The integral index in this study is considered as a quantitative assessment of the system-forming factor that determines the overall condition and sustainability potential of landscapes. System-forming factors, by definition, are properties of an object that are key to its functioning as part of a larger natural system [23].

An integral assessment of landscape stability to anthropogenic impact was conducted using a normalization and aggregation approach [24–27]. This method involves converting diverse indicators to a unified point scale, followed by their summation, enabling a comprehensive evaluation of geosystem stability and comparative analysis of territorial vulnerability [14,28].

The calculation of the integral indicator was carried out in several stages. Initially, each surveyed site was assigned a score from 1 to 5 for each indicator (Table 1), based on the intensity of the characteristic and its influence on landscape stability. Subsequently, the scores across all indicators were summed. The resulting total was then normalized as a percentage of the maximum possible score using the formula provided below [3].

$$C = \frac{\sum_{g=1}^n C_g}{Q} \times 100$$

where:

C—landscape stability score (%) with respect to anthropogenic impact; C_g —score assigned for each individual indicator; Q—maximum possible total score; g—ordinal number of the indicator; n—total number of indicators.

Such a point-index system enables landscapes to be classified by their level of stability (from very weak to relatively stable) and the results to be visualised in cartographic form. This method is widely used in domestic research and has proven to be an effective tool for analysing and comparing the stability of natural systems.

We propose dividing the total points obtained into four categories depending on the percentage of the maximum possible: the first category comprises very weakly stable landscapes (0–25%), the second category comprises weakly resistant landscapes (26–50%), the third category comprises moderately stable landscapes (51–75%), and the fourth category comprises relatively stable landscapes (76–100%).

Landscapes that are absolutely unstable, which would score zero points, do not exist, as do landscapes that are absolutely stable and would score the maximum amount of points.

Table 1. Scale of scoring of landscape resilience potential to anthropogenic impacts.

№	Indicator	Sustainability Scores				
		1	2	3	4	5
1	Relief type	Hilly	Hilly valley	Gentle-hilly	Flat and slightly undulating	Flat
2	Sum of active temperatures (>10 °C)	Very low	Low	Moderate	High	Very high
3	Annual precipitation (mm)	Very low	Low	Moderate	High	Very high
4	Slope steepness, °	More than 20°	5–20°	3–5°	1–3°	0–1°
5	Soil mechanical composition	Sand	Loam	Light loam	Medium loam	Heavy loam
6	Thickness of humus horizon (cm)	Mostly soil-free/Very little power (less than 10 cm)	Very severe limitations/Small power (10–20 cm)	Severe limitations/Medium power (20–40 cm)	Moderate limitations/Large power (40–60 cm)	Minor limitations/Very large power (more than 60 cm)
7	Soil moisture index	Very low	Low	Moderate	High	Very high
8	Degree of salinity	Very strong	Strong	Weak	Very weak	Not salted
9	Type of water regime	Deconstructive effusion	Effusion	Non-washing	Periodically flushing	flushing
10	Vegetation cover (projective coverage, %)	Uncovered	Weakly covered (less than 30)	Moderately covered (31–60)	Strongly covered (60–90)	Solidly covered (more than 90)

Selection of Indicators Based on Significance Criteria

Landscape stability results from the complex interplay between natural and anthropogenic factors. In developing the assessment framework, ten indicators were selected to capture essential aspects of geosystem structure, morphodynamics, and bioproductive capacity. The selection was guided by the following principles:

Priority was given to natural parameters that are critical under the arid conditions of the West Kazakhstan region. In particular, moisture regime and heat supply were considered key determinants of vegetation productivity [29]. Additionally, particle-size distribution and humus horizon thickness were included, as they influence soil buffering capacity and self-restoration potential. For instance, sandy massifs with low fine particle content and shallow humus layers exhibit markedly reduced resistance to erosion and aeolian deflation.

Secondly, morphometric indicators of the relief, including surface configuration and slope steepness, were identified as key factors. As noted by [30], slope gradient is a critical determinant of landscape stability, influencing both the direction and intensity of material transport, as well as the geosystem's capacity for self-purification. Steeper slopes accelerate surface runoff, enhance linear and sheet erosion, and impede the formation and recovery of the humus layer.

In the study area, which is predominantly characterized by flat and slightly undulating terrain, there are also zones of gently rolling and hilly plains that exhibit higher susceptibility to erosion. This variability provided a strong rationale for incorporating morphometric relief parameters into the landscape stability assessment framework.

The third group of indicators encompasses soil and hydrological conditions, including water regime type and salinity level. Effusion and desiccation regimes, prevalent across much of the study area, lead to salt accumulation in the upper soil horizons, thereby reducing ecosystem productivity and accelerating degradation processes. Salinity, in this context, serves as an integrated indicator of landscape sustainability, reflecting long-term environmental transformations.

The fourth group addresses the bioproductive potential of landscapes, particularly through projective vegetation cover, which reflects the capacity of plant communities to protect soils from degradation and regulate the hydrothermal regime. Greater vegetation density is associated with increased resistance to mechanical disturbance [31].

Furthermore, in line with the methodological approach proposed by Dmitriev et al. [20], and acknowledging the absence of a universal weighting system, all selected indicators were considered equally significant to ensure methodological transparency and reproducibility of results.

Finally, anthropogenic disturbance data, derived from the previously developed landscape transformation map by the authors [22], were incorporated as a key component to represent the current level of human impact. Integrating these data with natural characteristics enabled the construction of a comprehensive indicator system encompassing the principal dimensions of landscape sustainability.

In summary, the selected indicators capture the distinctive features of arid and semi-arid landscapes in the region including climatic constraints, soil vulnerability, bioproductive capacity, and degree of anthropogenic transformation ensuring a holistic and objective assessment of their resilience to external pressures.

3. Results

3.1. Landscape Sustainability Map

In order to identify spatial differences in landscape sustainability, the values of each of the ten selected indicators were assessed for landscape units located within the main natural zones of the West Kazakhstan region. Based on this analysis, each landscape unit was assigned a score ranging from 1 to 5.

Table 2 shows the indicator values and assigned scores for the landscape units. These values formed the basis for calculating the integral sustainability indicator and mapping the spatial distribution of the region's landscape sustainability classes.

The overall matrix includes more than 50 landscape types and subtypes, which are classified by morphological features (e.g., plain or mountainous), zonal affiliation (e.g., steppe, dry steppe, semi-desert or desert) and morphometric subclasses (e.g., lowland, upland or shallow hills). This section only presents a fragment of the sample, including one typical landscape from each class, subclass, and zonal type.

The created map of landscape resilience to anthropogenic impact (Figure 3) was developed based on a combined analysis of estimated indicators and a map of anthropogenic disturbance, which was used as a base layer. This made it possible to integrate not only the characteristics of the natural properties and potential of ecosystems, but also to take into account the actual distribution of the intensity of anthropogenic impacts, including agricultural development, industrial development, linear construction and other forms of landscape transformation.

Table 2. Indicators of the potential sustainability of landscapes.

No. of Landscapes on the Map	Relief Character, Height	Slope Steepness	Humus Horizon Thickness	Salinity Degree	Mechanical Composition of Soils	Amount of Precipitation	Sum of Average Daily Temperatures, Above 10 °C;	Vegetation Cover, Projective Cover %	Type of Water Regime	Soil Moisture Index
	1	2	3	4	5	6	7	8	9	10
					Class: Plain					
					Type: Steppe					
					Subclass: Elevated					
31	1	3	4	5	4	5	1	5	2	3
					Type: Steppe					
					Subclass: Low-hilly					
9	2	3	4	5	3	5	4	5	3	5
					Type: Dry steppe					
					Subclass: Low-lying					
1	5	5	4	5	5	5	2	4	4	4
					Type: Dry steppe					
					Subclass: Elevated					
2	3	3	5	5	3	5	2	5	4	3
					Type: Dry steppe					
					Subclass: Low-hilly					
34	2	4	4	4	3	4	1	4	2	3
					Type: Semi-desert					
					Subclass: Low-lying					
12	5	5	3	2	5	3	2	4	2	3
					Type: Semi-desert					
					Subclass: Elevated					
26	3	3	4	3	3	3	2	3	2	2
					Type: Semi-desert					
					Subclass: Low-hilly					
14	3	5	4	3	4	3	2	3	2	2
					Type: Desert					
					Subclass: Low-lying					
49	5	5	2	1	3	1	4	2	4	1
					Type: Desert					
					Subclass: Elevated					
16	3	4	3	3	4	2	3	3	2	1
					Type: Desert					
					Subclass: Low-hilly					
40	3	4	3	3	2	1	4	2	2	2
					Class: Mountainous					
					Type: Dry Steppe					
					Subclass: Low-mountain					
18	2	2	4	5	2	3	1	3	2	2
					Type: Desert					
					Subclass: Low-mountain					
19	3	4	3	4	3	1	4	2	2	2

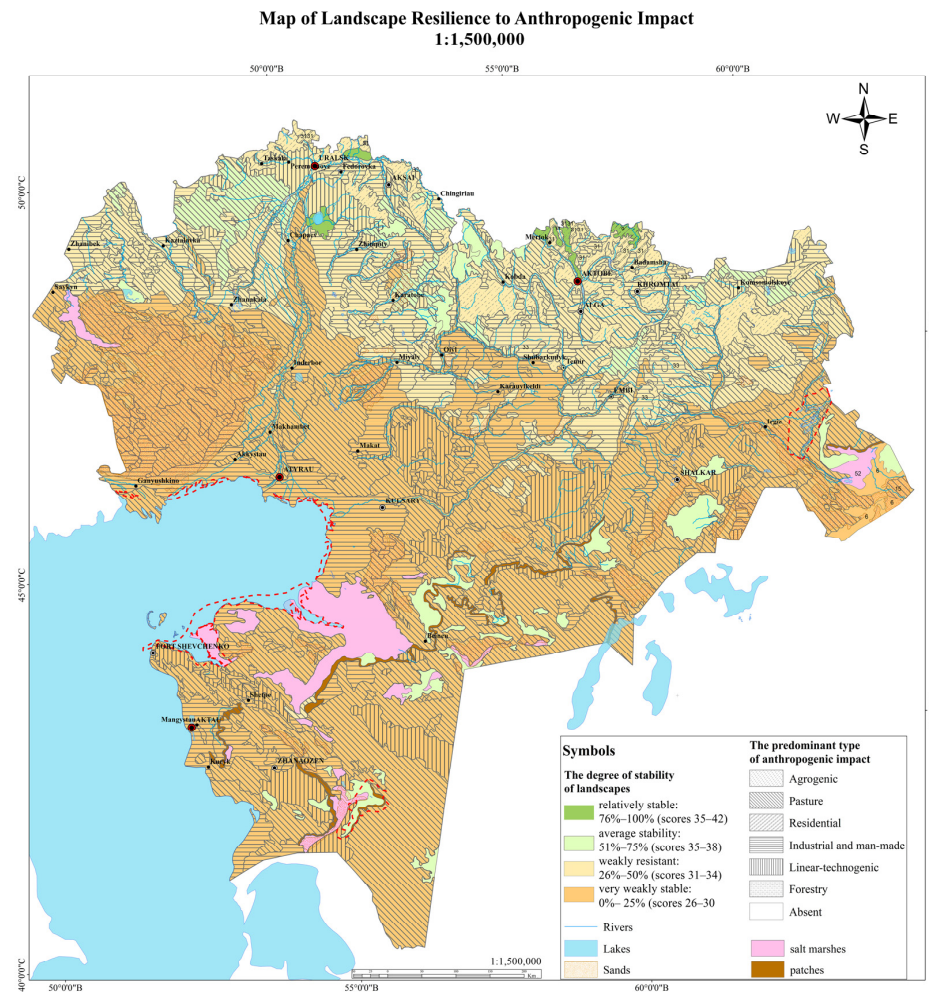


Figure 3. Map of landscape resilience to anthropogenic impact of the West Kazakhstan region.

3.2. Spatial Distribution of Stability Classes

The spatial distribution of landscape stability classes in the West Kazakhstan region (Figure 4) shows that the territory is clearly divided in terms of its vulnerability to human impact. The results of the integrated assessment identified four landscape stability classes: highly susceptible, low-resistant, medium-stability and relatively stable.

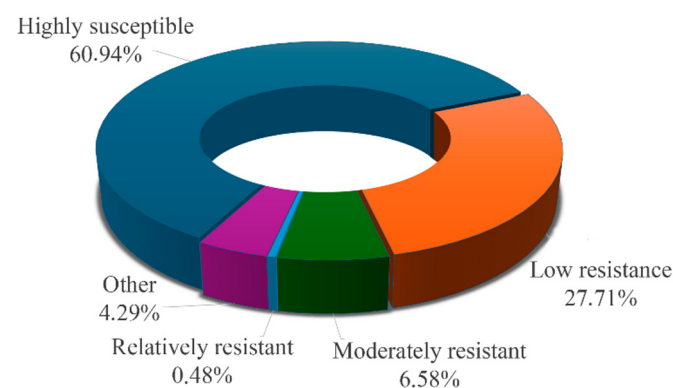


Figure 4. Ranking of landscape sustainability in the West Kazakhstan region by categories, %.

The most vulnerable categories, which cover over 60.0% of the area, are confined to the arid natural complexes of the semi-deserts and deserts, such as sandy massifs, salt flats, and arid intermountain depressions. These areas are characterised by light soil textures, low

humus content, high salinity, and sparse vegetation, which limits their ability to self-repair and makes them highly sensitive to degradation processes.

Weakly stable landscapes make up around 27.7% of the territory and are mainly found in steppe and semi-desert areas with automorphic soils and gentle slopes, as well as a more developed vegetation structure. However, they are also susceptible to anthropogenic pressure, particularly in areas of agricultural development.

Moderately resistant and relatively resistant landscapes, totalling no more than 11.0% of the region's area, are confined to the north and north-east, where natural conditions favour the preservation of ecosystem stability. These areas are characterised by loamy soils, increased phytocenosis productivity and poorly articulated relief, which contribute to a higher degree of stability.

Thus, despite the predominance of territories with low sustainability (making up around 88.0% of the total area), the region's structure retains areas with higher restoration potential. This must be considered when developing environmental monitoring and planning strategies.

3.3. Verification Using Remote Sensing Indices and Field Data:

3.3.1. Results of NDSI Analysis

To verify the spatial assessment of landscape stability, remote sensing data was used. In particular, a map of average soil salinity was calculated using the NDSI index for the period 2000–2024 (Figure 5). Analysis of the obtained data showed a pronounced correlation between areas with high salinity levels and territories classified as highly unstable landscapes based on the integral assessment results.

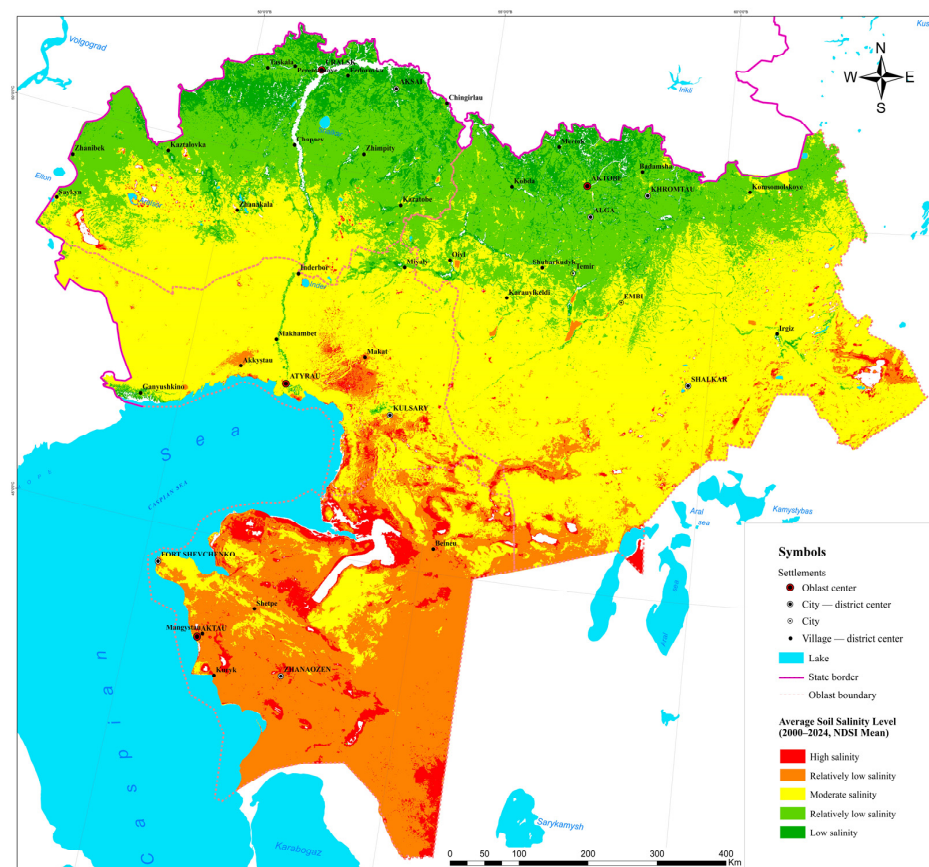


Figure 5. Map of Average Soil Salinity in Western Kazakhstan region based on the NDSI Index (2000–2024).

The largest areas with elevated salinity index values (ranging from yellow to red) are concentrated in the southern and southwestern regions, encompassing sandy massifs (Bolshie and Malye Barsuki), salt marshes (Chalkar and Inder), and the Caspian lowlands. These areas are characterised by salt accumulation in the soil profile, moisture deficiency, and high vulnerability to degradation processes. This is confirmed by their classification as weakly and very weakly stable landscapes on the final stability map.

Relatively favourable conditions with low salinity levels are evident in the northern and north-eastern parts of the region (shown in green and light green on the salinity map). These areas mostly coincide with those identified as medium-stable and relatively stable landscapes, confirming the accuracy of the integrated assessment.

Comparing cartographic data on salinity with field observations confirms that soil and vegetation degradation within arid complexes is a key factor in the instability of geosystems. The results obtained emphasise the importance of using remote sensing indexes as an independent data source to clarify the spatial distribution of stability classes and verify mapping results.

3.3.2. Results of NDVI Analysis

Analysis of the NDVI for the period 2000–2024 (Figure 6) revealed clear degradation of vegetation cover in arid and semi-arid zones. The time series shows persistently low NDVI values in the southern half of Western Kazakhstan, reflecting a decrease in biomass and the reduced ability of ecosystems to regenerate. Notably, vegetation distribution remained relatively stable between 2000 and 2008; however, since 2015, there has been an expansion of areas with low cover density, which increased by 2024. These changes are most pronounced in territories classified as weakly and very weakly stable in the integrated assessment.

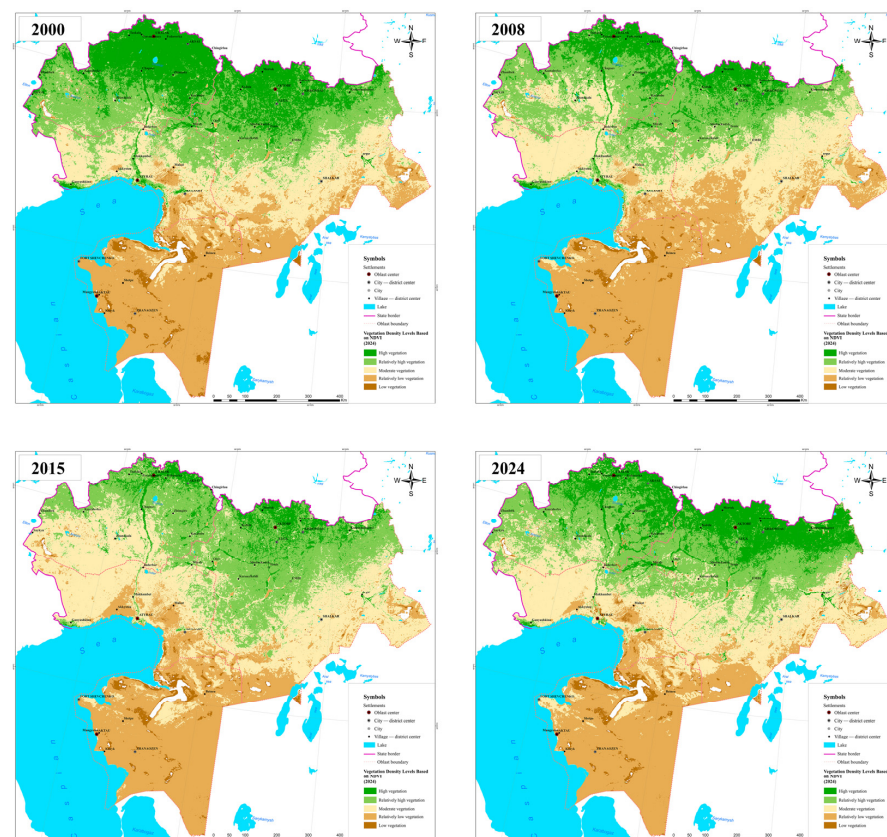


Figure 6. Map of vegetation cover in Western Kazakhstan (2000, 2008, 2015, 2024) based on the normalized difference vegetation index (NDVI).

3.3.3. Results of the Temperature Stability Analysis

In addition to assessing soil salinity and vegetation cover, the variability of the temperature regime was analysed for the period 2000–2024 based on ERA5-Land data, with the calculated coefficient of variation of active temperatures shown in Figure 7.

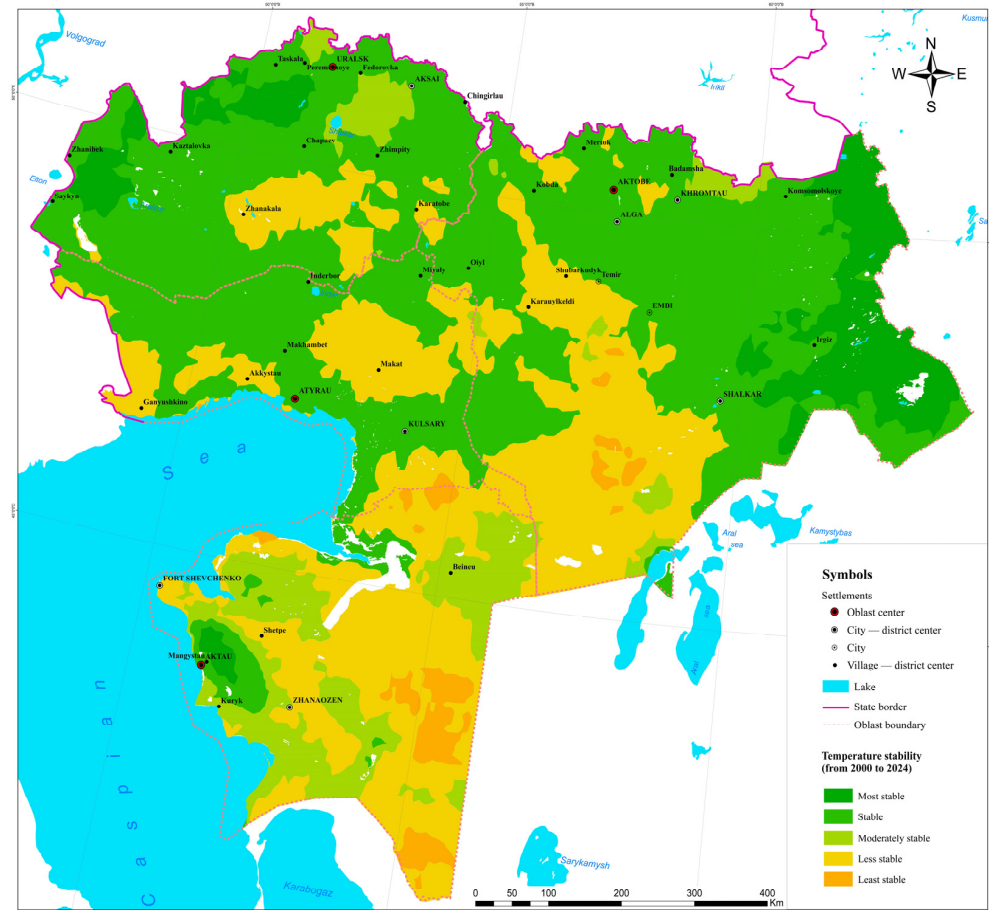


Figure 7. Map of temperature stability in Western Kazakhstan (2000–2024) based on the coefficient of variation (CV) of active temperature days (constructed using ERA5-Land data and climate variability analysis).

The temperature stability map shows that the southern and southwestern regions are the most unstable, with significantly higher values of the coefficient of variation of active temperatures than the average. This reflects pronounced climatic extremes, with alternating periods of high summer temperatures and prolonged dry phases. Relatively high temperature stability is observed in the northern and north-eastern parts of the territory, creating more favourable conditions for maintaining the productivity and regenerative abilities of ecosystems.

Comparing the data with the stability class map shows that areas with the most pronounced temperature instability mainly coincide with zones of unstable and very unstable landscapes. This confirms that temperature variability significantly increases the vulnerability of natural ecosystems to human impact. High temperatures and their fluctuations, in particular, accelerate the processes of degumification and soil salinisation, reduce projective cover, and increase the risk of erosion.

Therefore, temperature monitoring data are consistent with the results of the integrated assessment, confirming that climate variability, alongside soil and vegetation degradation, plays a key role in the spatial heterogeneity of landscape sustainability in the region.

3.3.4. Results of the Field Study

To verify the reliability of the integrated landscape stability assessment and the spatial distribution of stability classes, a series of field observations was conducted at eight key sites (see Figure 8). During the survey, local features of degradation processes characteristic of the different stability categories were recorded.

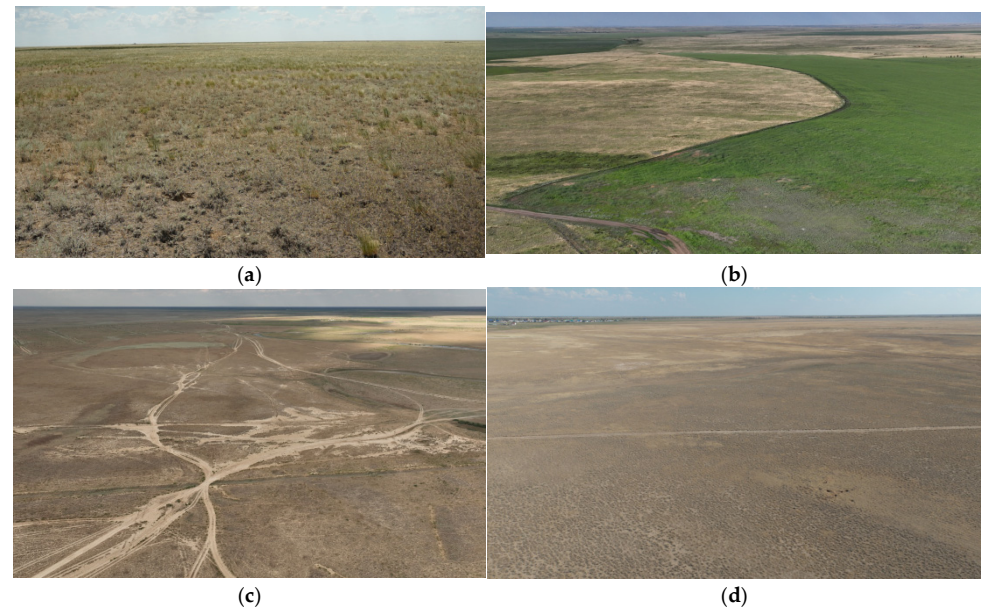


Figure 8. Field research. (a) West Kazakhstan region, Zhymпиты-Karatobe district, Description point Pw27. (b) Aktoobe region, Kargaly district, Description point Pw 15. (c) Atyrau region, Indersky district, Description point Pw 46. (d) Atyrau region, Indersky district, Description point Pw 45.

At point Pw27, located in the Zhymпиты-Karatobe area, signs of intensive pasture degradation were observed, including disturbed grass cover, soil compaction, and pronounced trampling marks. This site is classified as ‘slightly stable’ in the integrated classification, a classification that is generally confirmed by the results of the field survey, which showed that the ecosystem is highly sensitive to overgrazing.

The landscape in the Kagarlyk district of the Aktoobe region (point Pw15) is also classified as slightly stable. In fact, the entire area has been converted into arable land and hayfields. However, the steppe zone’s climatic conditions and moderately arid regime create favourable conditions for restoring vegetation with a reduction in anthropogenic pressure. Potential recultivation is possible here in the medium term.

Points Pw46 and Pw45, located in the Inder district of the Atyrau region, demonstrate the existence of highly unstable landscapes. Field surveys revealed extreme soil and vegetation destruction, as well as numerous traces of machinery and linear infrastructure. These findings are consistent with the low stability zones identified on the map.

In the Mangystau region, areas Pw57 (in the Beineu district), Pw62 (in the Munaily district) and Pw63 (in the Karakiya district, at the Zhetibay oil field) also exhibited significant levels of degradation. The Pw57 area is characterised by a sandy desert with sparse vegetation and large open sandy areas, reflecting the vulnerability of ecosystems to grazing and climatic extremes. At Pw62 and Pw63, intensive industrial and transport exploitation was evident in the form of numerous dirt roads, surface compaction and mechanical destruction, as well as an absence of regenerating vegetation. This is particularly evident at site Pw63, where there is complete bare soil and clear signs of long-term oil production.

Comparing the integrated sustainability map with remote sensing data and field survey results revealed a high degree of spatial consistency between areas of low sustainability

and zones experiencing vegetation degradation, increased soil salinity and climatic instability. These verification results confirm that the integrated assessment accurately reflects the current state of the region's ecosystems, providing an opportunity to objectively identify areas in need of priority monitoring, protection, and restoration.

3.4. Characteristics of Zones with Differentiated Stability

To analyse variations in landscape stability, a selected fragment of the study area (Figures 9 and 10) was examined in detail. This approach enabled a more detailed assessment of spatial differentiation in ecosystem resilience, as well as the identification of zones requiring priority monitoring and protection.

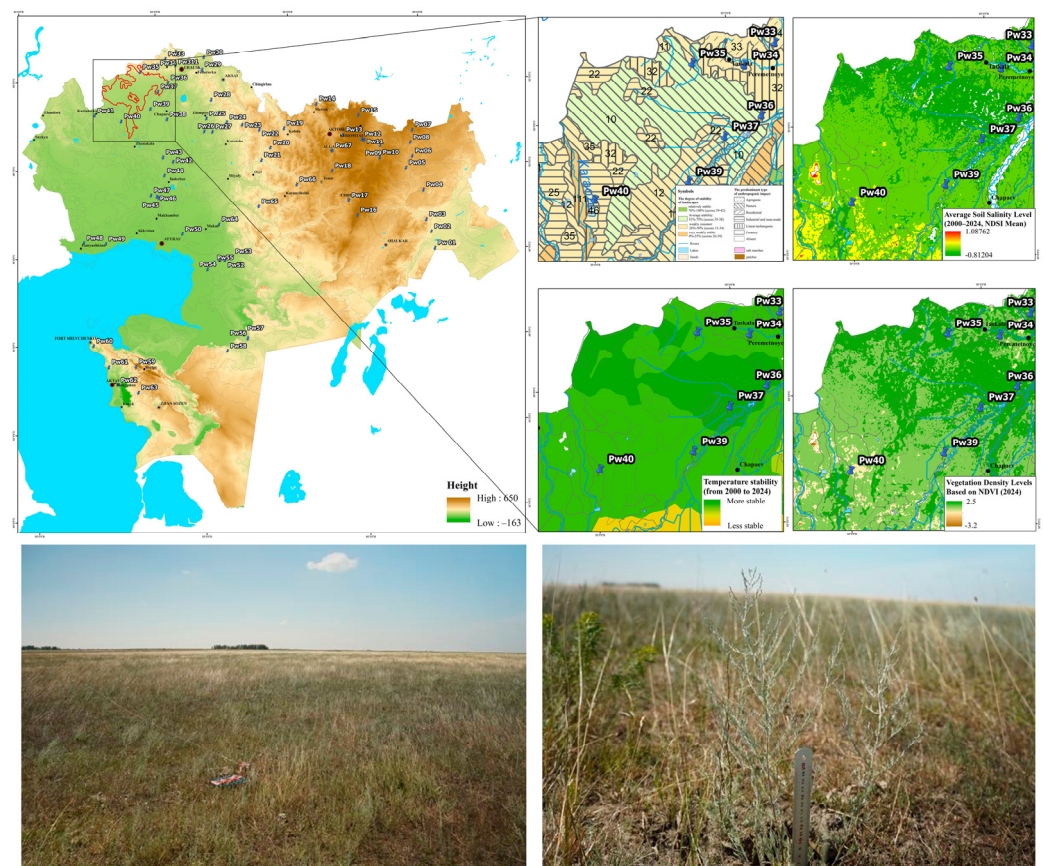


Figure 9. West Kazakhstan Region, Taskaly District, Description point Pw 35, zone of medium stability.

Case studies of sites Pw 62, Pw 63 and Pw 35 revealed the key factors that influence ecosystem stability and vulnerability. Analysis of NDVI and NDSI showed significant differences: sites Pw 62 and Pw 63, which were classified as having very weak stability, exhibited low NDVI values and high soil salinity, as confirmed by field data (Table 3). These indicators suggest advanced soil and vegetation degradation and low potential for natural regeneration.

By contrast, plot Pw 35, which is classified as moderately stable, exhibits significantly higher NDVI values and low salinity, suggesting improved vegetation health and greater ecological stability.

Therefore, by comparing data from these indices with field observations, we can establish the causal relationships between sustainability levels, soil and vegetation conditions, and the nature of the anthropogenic impact.

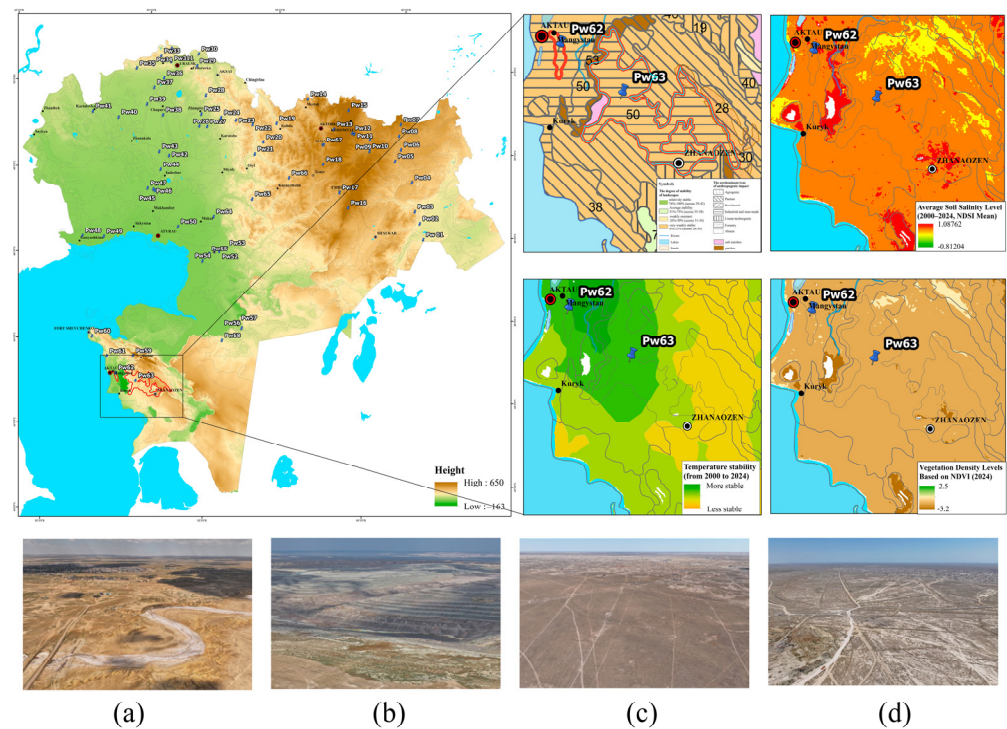


Figure 10. (a,b) Mangystau region, Munaily district, Description point Pw 62; (c,d) Mangystau region, Karakiya district (Zhetibay), Description Pw point 63, low-resistant zone.

Table 3. Comparative characteristics of surveyed/verified sites by degree of stability.

Key Points	Degree of Stability	Final Sustainability Score	NDVI Value	NDSI Value	Active Temperature Values	Field Research
Pw 35	Moderately resistant	35	0.344692	−0.353847	0.047084	Pasture use, without significant traces of ecosystem degradation or destruction.
Pw 62	Low resistant	28	0.128192	−0.114901	0.047491	Significant degradation of the soil and vegetation cover. Processes of soil salinization, erosion and deflation. Intensive industrial use.
Pw 63	Low resistant	26	0.131317	−0.117126	0.047491	Significant landscape degradation. Development of hydrocarbon deposits. Ecosystem stability significantly reduced.

4. Discussion

The findings confirm that in the arid and semi-arid landscapes of Western Kazakhstan, the stability of natural systems is governed by both climatic and anthropogenic influences. In contrast to previous generalized regional assessments [11,31], this study is the first to implement a spatially explicit approach integrating remote sensing data and field observations at the level of individual landscape units.

The analysis identified key natural constraints on sustainability, including pronounced aridity, seasonal temperature extremes, limited soil regeneration potential, and localized salinization, particularly in lowland areas. The most vulnerable zones were flat semi-arid and arid landscapes with degraded vegetation cover, where NDVI values fell below 0.2 and NDSI indicated trends toward secondary salinization (sites Pw 63, Pw 45).

Steppe and dry steppe landscapes with small hills and elevated relief forms, which have better drainage and denser vegetation cover ($\text{NDVI} > 0.3$), such as in section Pw 35, proved to be relatively more stable. Here, anthropogenic impact, mainly grazing, has a less destructive effect, which is consistent with the conclusions [32] emphasising moderate grazing as an acceptable load for agro-pastoral ecotones.

A comparison with the studies by Chen et al. [33] and Khaitbaev et al. [34] shows that the general problems of landscape degradation in Central Asian countries are similar in nature but manifest themselves differently. In Uzbekistan, the main pressure is related to irrigation and secondary salinisation in oasis systems, while in Western Kazakhstan, the priority factors are extensive grazing and the technogenic load from the oil and gas industry.

The practical significance of the study lies in the fact that the constructed sustainability map allows for the identification of areas with varying degrees of vulnerability and the justification of priority zones for reclamation, restrictions on economic activity, or environmental monitoring. The methodology tested in Western Kazakhstan can be scaled up to other arid areas, as demonstrated in [35] as part of the sustainability assessment in the China–Mongolia–Russia economic corridor.

Recommendations Based on Landscape Sustainability Classes

Based on the research conducted, an action plan was proposed that includes measures to manage the sustainability of landscapes in Western Kazakhstan depending on the identified sustainability classes: very low sustainability, low sustainability, medium sustainability, and relatively high sustainability. This approach allows for the precise targeting of environmental protection, restoration and regulatory actions corresponding to the actual state of the geosystem and the specifics of land use.

The proposed implementers of these measures are:

- Territorial divisions of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan,
- Local executive bodies (district and regional akimats),
- Specialised departments of the Ministry of Agriculture of the Republic of Kazakhstan,
- Scientific institutions and universities,
- International and national sustainable development funds (UNDP, GEF, etc.).

Highly unstable landscapes:

Declaration of strictly regulated zones, prohibiting agricultural exploitation and industrial development.

- Implementation of comprehensive restoration measures, such as planting stable vegetation, combatting deflation and erosion, and carrying out drainage works.
- Continuous monitoring using satellite data (NDVI, NDSI) and regular field surveys.

Launch pilot restoration projects in the most affected areas (e.g., Pw62, Pw63).

Weakly stable landscapes:

- Limited economic use with mandatory load regulation.
- Introduction of adaptive forms of land use, such as pasture rotation, soil protection and phytomelioration.
- Creation of local regulations for nature use, taking sustainability maps into account.

Support for farmers through sustainable agriculture and ecosystem services programmes.

Moderately resistant landscapes:

- Permitted rational use in compliance with environmental requirements.
- Measures to support ecosystem sustainability include the restoration of vegetation cover and the prevention of local erosion.
- Promotion of agroecological practices.
- Development of a system for assessing the state of the landscape and responding early to degradation processes.

Relatively stable landscapes:

- Preservation as reference territories for monitoring and research.
- Control over the prevention of degradation, including limiting anthropogenic load and protecting biodiversity.
- Use for demonstration and educational purposes.
- Maintaining the current condition with periodic environmental assessment.

In Western Kazakhstan, up to 45% of the rural population is engaged in pastoral animal husbandry, which dominates the economy of the districts. The degradation of natural complexes reduces productivity and increases the population's dependence on climate risks. Therefore, implementing this strategy will improve the well-being of rural communities by improving land quality, creating employment opportunities and ensuring the sustainability of ecosystem services.

The proposed spatially oriented strategy will enable resources to be effectively directed towards the protection and restoration of vulnerable landscapes, and will integrate scientific data into the spatial planning system, ensuring coordinated interaction between all levels of government and local communities. Implementing the proposed differentiated strategy will enhance the environmental efficiency of land management, prevent ecosystem degradation, and ensure the region's sustainable development based on scientifically sound spatial data.

5. Conclusions

This study developed and tested a comprehensive methodology for assessing landscape sustainability in Western Kazakhstan, incorporating both natural and anthropogenic parameters. The approach is based on a multi-criteria framework that integrates remote sensing data, field survey results, and GIS-based spatial analysis.

The novelty of the methodology lies in the integration of geoecological, climatic, and socio-economic indicators into a unified assessment system. The selection of indicators, scoring criteria, and spatial analysis methods was tailored to the specific conditions of the region's arid and semi-desert landscapes, enabling a spatially explicit evaluation across more than 50 landscape types and subtypes.

A spatial assessment of landscape sustainability was conducted for the first time in the Western region using remote sensing data and field surveys. A landscape sustainability map was compiled to allow visualisation of spatial differentiation by degree of vulnerability. The spatial analysis revealed areas of extremely low sustainability, primarily in semi-arid and arid regions subject to high grazing pressure and water shortages. This is due to their natural aridity and high sensitivity to human impact.

Based on the obtained data, an action plan for land resource management was developed that takes sustainability classes into account. Measures for the conservation, restoration and sustainable use of territories, adapted to regional conditions, were proposed.

The results of the study are important for practical applications such as spatial planning, monitoring degradation and developing sustainable land use programmes and environmental policy in arid regions. The maps and recommendations presented can be

used by local authorities, environmental departments, non-governmental organisations and international institutions.

Author Contributions: Conceptualization, A.T. and A.R.; methodology, A.T. and I.S.; software, D.K. and A.B.; validation, A.M. and I.S.; formal analysis, D.K. and U.M.; investigation, A.R., A.M. and B.B.; resources, B.B. and U.M.; data curation, A.B. and I.S.; writing—original draft preparation, A.M. and A.R.; writing—review and editing, A.M. and I.S.; visualization, A.R. and D.K.; supervision, A.T.; project administration, A.T.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882122 “Sustainable development of natural-industrial and socio-economic systems of the West Kazakhstan region in the context of green growth: a comprehensive analysis, concept, forecast estimates and scenarios”).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Merekalova, K.A.; Kharitonova, A.O. Integral Stability and Natural Potential of Landscapes in Southeastern Crimea. In *Landscape Science: Theory, Methods, Landscape-Ecological Support of Land Use and Sustainable Development: Proceedings of the XII International Landscape Conference, Tyumen–Tobolsk, 22–25 August 2017*; Tyumen State University Publishing House: Tyumen, Russia, 2017; Volume 2, pp. 163–168. Available online: https://www.researchgate.net/profile/Jacek-Kwiatkowski-4/publication/375232677_SUSTAINABLE_TOURISM_-_A_CONSERVATION_OF_NATURAL_AND_CULTURAL_RESOURCES_OF_THE_TRANSBOUNDARY_REGION_OF_THE_LANDSCAPE_PROTECTED_DISTRICT_OF_ROMINTEN_FOREST_POLAND_-_KALININ_GRAD_OBLAST/links/654440fab1398a779d51e51a/SUSTAINABLE-TOURISM-A-CONSERVATION-OF-NATURAL-AND-CULTURAL-RESOURCES-OF-THE-TRANSBOUNDARY-REGION-OF-THE-LANDSCAPE-PROTECTED-DISTRICT-OF-ROMINTEN-Forest-Poland-KALININGRAD-OBLAST.pdf (accessed on 26 July 2025). (In Russian)
2. Khavanskaya, N.M. Methodological Approaches to the Assessment of Geosystem Stability to Mining Industry Impacts. *Vestn. Volgogr. Gos. Univ. Ekon.* **2011**, *3*, 254–257. Available online: <https://cyberleninka.ru/article/n/metodicheskie-podhody-k-otsenke-ustoychivosti-geosistem-k-vozdeystviyu-dobyvayuschey-promyshlennosti> (accessed on 26 July 2025). (In Russian)
3. Orlova, I.V. *Landscape-Agroecological Planning of the Territory of a Municipal District*; Krasnoyarsk, B.A., Ed.; Siberian Branch of the Russian Academy of Sciences, Institute for Water and Environmental Problems: Novosibirsk, Russia, 2014; 254p, Available online: http://www.old.iwep.ru/ru/struct/LLVEP/publ_Orlova/MonografiyaLandshaftno-agroekologicheskoe.pdf (accessed on 26 July 2025). (In Russian)
4. Glazovskaya, M.A. *Methodological Basis for Assessing Ecological and Geochemical Soil Resistance to Technogenic Impacts*; Moscow State University Publishing: Moscow, Russia, 1997; 102p. Available online: <https://istina.msu.ru/publications/book/637785042/> (accessed on 26 July 2025). (In Russian)
5. Solntseva, N.P. Geochemical Stability of Natural Systems to Technogenic Loads. In *Mineral Extraction and Geochemistry of Natural Ecosystems*; Nauka: Moscow, Russia, 1982. Available online: <https://www.geokniga.org/bookfiles/geokniga-dobychapoleznyhi-skopaemyhigeohimiyaprirodnih ekosistem.pdf> (accessed on 26 July 2025). (In Russian)
6. Armand, A.D. Stability (Homeostasis) of Geographic Systems to Various Types of External Influences. In *Stability of Geosystems*; Nauka: Moscow, Russia, 1983; pp. 50–61.
7. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
8. Tumel, N.V. *Geocology of the Cryolithozone*, 2nd ed.; Yurayt: Moscow, Russia, 2017; 244p. Available online: https://istina.msu.ru/media/publications/book/f6a/2fa/7060966/Geoekologiya_kriolitozonyi_2014.pdf (accessed on 26 July 2025). (In Russian)
9. Wu, J. Key concepts and research topics in landscape ecology revisited: 30 years after the Allerton Park workshop. *Landscape Ecol.* **2013**, *28*, 1–11. [CrossRef]
10. Breckle, S.W.; Veste, M.; Wucherer, W. (Eds.) *Sustainable Land Use in Deserts*; Springer: Berlin/Heidelberg, Germany, 2012. [CrossRef]

11. Reynolds, J.F.; Stafford Smith, D.M.; Lambin, E.F.; Turner, B.L., 2nd; Mortimore, M.; Batterbury, S.P.; Downing, T.E.; Dowlatabadi, H.; Fernández, R.J.; Herrick, J.E.; et al. Global desertification: Building a science for dryland development. *Science* **2007**, *316*, 847–851. [CrossRef]
12. Berdugo, M.; Delgado-Baquerizo, M.; Soliveres, S.; Hernández-Clemente, R.; Zhao, Y.; Gaitán, J.J.; Gross, N.; Saiz, H.; Maire, V.; Lehmann, A.; et al. Global ecosystem thresholds driven by aridity. *Science* **2020**, *367*, 787–790. [CrossRef] [PubMed]
13. Kashkinbekov, A. Global Trends: Greentech & Investment Projects in Kazakhstan. In Proceedings of the 3rd IAEE Eurasian Conference, Baku, Azerbaijan, 18–20 October 2018. Available online: <https://www.iaee.org/proceedings/article/16366> (accessed on 26 July 2025). (In Russian)
14. Ozgeldinova, Z.O.; Mukaev, Z.T.; Ospan, G.T. Assessment of Geosystem Resilience under Anthropogenic Impacts: A Case Study of the Sarysu River Basin. *Gidrometeorol. Ekol.* **2020**, *3*, 19–33. Available online: <https://journal.kazhydromet.kz/kazgidro/article/view/194/2090> (accessed on 26 July 2025). (In Russian)
15. Mazhitova, G.Z.; Dzhanaleyeva, K.M. Analysis of the Landscape Structure of the Steppe Zone of the North Kazakhstan Region. *J. Geogr. Environ. Manag.* **2018**, *48*, 14–21. Available online: <https://bulletin-geography.kaznu.kz/index.php/1-geo/article/view/483> (accessed on 26 July 2025). (In Russian)
16. Pachikin, K.M.; Erokhina, O.G.; Ershibulov, A.K.; Songulov, E.E. Modern Approaches to Land Resource Assessment: A Case Study of Western Kazakhstan. *Soil Sci. Agrichem.* **2024**, *2*, 105–116. (In Russian) [CrossRef]
17. Nasiev, B.N.; Bekkaliev, A.K. *Pasture Ecosystems of Western Kazakhstan: Current State and Rational Use Technologies*; ZKGU Publishing: Uralsk, Kazakhstan, 2020. Available online: <https://e.lanbook.com/book/176755?category=939&publisher=20501> (accessed on 26 July 2025). (In Russian)
18. Geldyeva, G.V.; Zubakin, M.Y.; Shparfov, A.A. Cartographic Support for Landscape-Ecological Stability of Hydrocarbon Production, Processing and Transportation Areas Using Remote Sensing and GIS. *InterKarto. InterGIS* **2015**, *21*, 74–81. Available online: <http://intercarto.msu.ru/jour/data/p0/article150.pdf> (accessed on 26 July 2025). (In Russian) [CrossRef]
19. Ogurtsov, A.N.; Dmitriev, V.V. Geoinformation Analysis of the Biological Efficiency Index of Climate as a Criterion for Assessing Potential Landscape Resilience. *InterKarto. InterGIS* **2017**, *23*, 191–204. Available online: <https://doi.org/10.24057/2414-9179-2017-1-23-191-204> (accessed on 26 July 2025). (In Russian) [CrossRef]
20. Dmitriev, V.V.; Ogurtsov, A.N.; Morozova, A.S.; Pilyugina, A.A.; Sverdlova, O.A.; Sirotina, P.M.; Fedorova, M.E.; Cherepanov, S.V.; Shakurov, V.A. Integral Assessment of Landscape Resilience: Models, Results, Perspectives. *Mezhdunar. Zhurnal Prikl. I Fundam. Issled.* **2017**, *9*, 110–114. Available online: <https://s.applied-research.ru/pdf/2017/9/11837.pdf> (accessed on 26 July 2025). (In Russian)
21. Corbel, J. Erosion in Limestone Terrain: Rate of Erosion and Morphology. *Ann. Geogr.* **1959**, *68*, 97–120. Available online: https://www.persee.fr/doc/geo_0003-4010_1959_num_68_366_16541 (accessed on 26 July 2025). (In French) [CrossRef]
22. Tokbergenova, A.; Skorintseva, I.; Ryskeldiyeva, A.; Kaliyeva, D.; Salmurzauly, R.; Mussagaliyeva, A. Assessment of Anthropogenic Disturbances of Landscapes: West Kazakhstan Region. *Sustainability* **2025**, *17*, 573. [CrossRef]
23. Kazantseva, O.I. Nauchnye idei L.S. Scientific Ideas of L.S. Berg and Approaches to Developing Indicators of Sustainable Development. In *Academician Leo Berg–130: Collection of Scientific Articles*; Eco-TIRAS: Bender, Moldova, 2006; pp. 265–274. Available online: <https://eco-tiras.org/docs/Berg-book.pdf> (accessed on 26 July 2025). (In Russian)
24. Kochurov, B.I. New Geoecological and Socio-Ecological Terms and Concepts. *Probl. Region. Ekol.* **1997**, *3*, 5–12. (In Russian)
25. Bashkin, V.N.; Evstaf'eva, E.V.; Snakin, V.V.; Alyabina, I.O.; Antipova, A.V.; Brazhnikova, O.I.; Vorob'ev, V.V.; Vorob'eva, I.B.; Galiulin, R.V.; Dubinina, S.S.; et al. *Biogeochemical Bases of Environmental Regulation*; Nauka: Moscow, Russia, 1993; 312p. Available online: https://books.google.kz/books/about/%D0%91%D0%B8%D0%BE%D0%B3%D0%B5%D0%BE%D1%85%D0%B8%D0%BC%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%B8%D0%B5_%D0%BE%D1%81%D0%BD.html?id=pAQEAQAAIAAJ&redir_esc=y (accessed on 26 July 2025). (In Russian)
26. Orlova, I.V. Landscape Planning for Sustainable Agricultural Land Use. *Geogr. Prir. Resur.* **2006**, *2*, 121–134. (In Russian)
27. Antyufeeva, T.V. Anthropogenic Transformation of Natural Complexes in Mining Areas. Ph.D. Thesis, Altai State University, Barnaul, Russia, 2004. Available online: <https://www.dissercat.com/content/antropogennaya-transformatsiya-prirodnikh-kompleksov-v-gornorudnykh-raionakh> (accessed on 26 July 2025). (In Russian)
28. Dobrovolskii, V.V. *Soil Geography with Fundamentals of Soil Science*; Vysshaya Shkola: Moscow, Russia, 1989; p. 320. Available online: https://chembaby.ru/wp-content/uploads/2015/10/Dobrovolskiy_VV_Geografia_pochv_s_osnovami_poch.pdf (accessed on 26 July 2025). (In Russian)
29. Bi, X.; Zhang, W.; Zhang, S.; Li, J.; Liu, L.; Li, X. Assessing Ecosystem Service Trade-Offs Driven by Land-Use Change in Arid Regions: A Case Study in the Hexi Corridor, China. *Ecol. Indic.* **2021**, *125*, 107511.
30. Dmitrieva, M.V.; Barmin, A.N.; Buziakova, I.V. Ecological Resilience of the Astrakhan Region to Technogenic Impact. *Geol. Geogr. Glob. Energy* **2014**, *4*, 91–99. Available online: [https://geo.asu-edu.ru/files/4\(55\)/91-99.pdf](https://geo.asu-edu.ru/files/4(55)/91-99.pdf) (accessed on 26 July 2025). (In Russian)

31. Didenko, P.A.; Vodopyanova, D.S.; Skripchinskaya, E.A. Assessment of Landscape Stability in the Stavropol Region to Anthropogenic Load. *Nauka. Innovatsii. Tekhnologii* **2018**, *2*, 127–138. Available online: <https://scienceit.elpub.ru/jour/article/view/203> (accessed on 26 July 2025). (In Russian)
32. Peng, J.; Chen, Y.; Liu, Y.; Lv, H.; Hu, X. Linking ecosystem services and landscape patterns to assess urban ecosystem health: A case study in Shenzhen City, China. *Landsc. Urban Plan.* **2015**, *143*, 56–68. [[CrossRef](#)]
33. Chen, T.; Zhang, Y.; Zhang, X.; Sun, R.; Huang, Q. Disentangling the relative impacts of climate change and human activities on arid and semiarid grasslands in Central Asia during 1982–2015. *Sci. Total Environ.* **2019**, *653*, 1311–1325. [[CrossRef](#)]
34. Khaitbaev, A.; Tukhliyev, A.; Baydullaev, R.; Nazarov, M. Anthropogenic transformation of oasis landscapes in Khorezm Province, Uzbekistan: A geoecological analysis. *E3S Web Conf.* **2024**, *497*, 02043. [[CrossRef](#)]
35. Abalakov, A.D.; Lopatkin, D.A.; Novikova, L.S. Stability of Landscapes in the Areas of Creation of Economic Corridors “China-Mongolia-Russia”. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *190*, 012022. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.