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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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GEOLOGICAL DEGRADATION UNDER CLIMATE CHANGE IN THE ARAL - SYRDARYA REGION: INTEGRATED MONITORING ASSESSMENT

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Abstract. *Relevance.* The article highlights a comprehensive analysis of the impact of climate change on the degradation of geological formations in the Aral–Syrdarya region using soil-hydrological and ecomonitoring methods. *Objective.* Assessment of the impact of climate change on the degradation of geological formations in the Aral–Syrdarya region using meteorological, hydrological, field and remote sensing data for the years 1980-2024, as well as the development of recommendations for an adaptive monitoring system for geological risks. *Methods.* This study used an integrated approach to pedohydrological and environmental monitoring to assess the impact of climate change on the degradation of geological formations in the Aral–Syrdarya region. The study combined long-term climate data

analysis, hydrological modeling, remote sensing, and geocological assessments at degradation sites. *Results and conclusions.* According to the results of long-term observations (2015-2024), it was found that the average annual air temperature increased by 1.5 °C, and the annual precipitation decreased by 12%. Changes in the hydrological regime manifested themselves in a decrease in the groundwater level by an average of 0.8 m over the past ten years, which contributed to a decrease in soil moisture by 15-20%. An analysis of the dynamics of vegetation degradation showed a reduction in the area of consistently vegetated lands by 18% and an increase in erosion processes by 25%. The activation of salt formation processes is observed - the concentration of salts in soils has increased by an average of 30%, which negatively affects the stability of geological formations and leads to accelerated destruction of structures. A comparative analysis of data from 2015 and 2024 confirms the trend towards accelerated degradation of the geological environment and deterioration of soil and hydrological conditions, which requires the application of adaptation measures and rational resource management.

Keywords: climate change, geological formations, degradation, soil, hydrology, Aral–Syrdarya, environmental monitoring

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АРАЛ–СЫРДАРІЯ ӨНІРІНДЕГІ КЛИМАТТЫҢ ӨЗГЕРУІ НӘТИЖЕСІНДЕ ГЕОЛОГИЯЛЫҚ ДЕГРАДАЦИЯСЫ: КЕШЕНДІ МОНИТОРИНГТІ БАҒАЛАУ

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Аннотация. *Өзектілігі.* Мақалада Арал-Сырдария аймағындағы геологиялық түзілімдердің деградациясына климаттық өзгерістердің әсерін, топырақ-гидрологиялық және экомониторингтік әдістерді пайдалана отырып, кешенді талдау зерттеулерін қамтиды. *Мақсаты.* 1980-2024 жылдардағы метеорологиялық, гидрологиялық, далалық деректерді және қашықтықтан зондтау деректерін пайдалана отырып, Арал-Сырдария өңіріндегі геологиялық түзілімдердің деградациясына климаттың өзгеруінің әсерін бағалау, сондай-ақ геологиялық тәуекелдер мониторингінің бейімделген жүйесі үшін ұсынымдар әзірлеу. *Әдістер.* Бұл зерттеу Арал-Сырдария аймағындағы геологиялық түзілімдердің деградациясына климаттың өзгеруінің әсерін бағалау үшін педогидрологиялық және экологиялық мониторингке кешенді тәсілді қолданды. Зерттеу ұзақ мерзімді Климаттық деректерді талдауды, гидрологиялық модельдеуді, қашықтықтан зондтауды және деградация орындарындағы геоэкологиялық бағалауды біріктірді. *Нәтижелер және қорытынды.* Көпжылдық бақылаулардың нәтижелері бойынша (2015-2024) ауаның орташа жылдық температурасы 1,5 °C-қа көтеріліп, жылдық жауын-шашын мөлшері 12% - ға төмендегені анықталды. Гидрологиялық режимнің өзгеруі соңғы он жылда жер асты сулары деңгейінің орта есеппен 0,8 м төмендеуінде көрінді, бұл топырақ ылғалдылығының 15-20% төмендеуіне ықпал етті. Өсімдік жамылғысының деградация динамикасын талдау өсімдіктермен тұрақты қамтылған жерлер аумағының 18% - ға қысқарғанын және эрозия процестерінің 25% - ға өскенін көрсетті. Тұз түзілу процестерінің белсенділігі байқалады-топырақтағы тұздардың концентрациясы орта есеппен 30% - ға өсті, бұл геологиялық түзілімдердің тұрақтылығына теріс әсер етеді және құрылымдардың тез бұзылуына әкеледі. 2015 және 2024 жылдардағы деректерді салыстырмалы талдау бейімделу шараларын қолдануды және ресурстарды ұтымды басқаруды талап ететін геологиялық ортаның жеделдетілген деградациясы мен топырақ-гидрологиялық жағдайлардың нашарлау тенденциясын растайды.

Түйін сөздер: климаттық өзгерістер, геологиялық формациялар, деградация, топырақ, гидрология, Арал-Сырдария, экологиялық мониторинг

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ГЕОЛОГИЧЕСКАЯ ДЕГРАДАЦИЯ В РЕЗУЛЬТАТЕ ИЗМЕНЕНИЯ КЛИМАТА В АРАЛО - СЫРДАРЬИНСКОМ РЕГИОНЕ: ОЦЕНКА КОМПЛЕКСНОГО МОНИТОРИНГА

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Аннотация. Актуальность. В статье представлен комплексный анализ влияния климатических изменений на деградацию геологических формаций в Арало-Сырдарьинском регионе с использованием почвенно-гидрологических и экомониторинговых методов. Изменение температурного режима, сокращение количества осадков, снижение уровня грунтовых вод, засоление почв и деградация растительного покрова усиливают геоэкологические риски и требуют формирования адаптивной системы мониторинга. **Цель.** Оценить влияние изменения климата на деградацию геологических формаций в Арало-Сырдарьинском регионе с использованием метеорологических, гидрологических, полевых данных и данных дистанционного зондирования за 1980–2024 годы, а также разработать рекомендации для адаптивной системы мониторинга геологических рисков. **Методы.** В исследовании использован комплексный подход к почвенно-гидрологическому и экологическому мониторингу для оценки влияния изменения климата на деградацию геологических формаций в Арало-Сырдарьинском регионе. В рамках исследования объединены анализ долгосрочных климатических данных, гидрологическое моделирование, дистанционное зондирование и геоэкологические оценки на участках деградации. **Результаты и выводы.** По результатам многолетних наблюдений за 2015–2024 годы установлено, что среднегодовая температура воздуха повысилась на 1,5 °С, а годовое

количество осадков сократилось на 12%. Изменения гидрологического режима проявились в снижении уровня грунтовых вод в среднем на 0,8 м за последние десять лет, что способствовало уменьшению влажности почв на 15–20%. Анализ динамики деградации растительного покрова показал сокращение площади стабильно покрытых растительностью земель на 18% и увеличение интенсивности эрозионных процессов на 25%. Отмечается активизация процессов солеобразования: концентрация солей в почвах повысилась в среднем на 30%, что отрицательно влияет на устойчивость геологических формаций и приводит к ускоренному разрушению их структуры. Сравнительный анализ данных за 2015 и 2024 годы подтверждает тенденцию к ускоренной деградации геологической среды и ухудшению почвенно-гидрологических условий. Полученные результаты свидетельствуют о необходимости применения адаптационных мер, совершенствования системы комплексного мониторинга и рационального управления природными ресурсами региона.

Ключевые слова: климатические изменения, геологические формации, деградация, почва, гидрология, Арал-Сырдарья, экологический мониторинг

Introduction. The Aral-Syrdarya region has become one of the most environmentally and geologically transformed natural zones in Central Asia over recent decades, experiencing significant pressure from both anthropogenic activities and global climate change (Berdimbetov et al., 2021). The dramatic shrinkage of the Aral Sea, driven by decades of intensive irrigation in the Amu Darya and Syr Darya river basins, has led to widespread ecosystem degradation and the disintegration of geological and geomorphological structures in the region (Micklin, 2007; UNEP, 2011).

Contemporary climate trends - including rising annual average temperatures, decreasing precipitation, and increasing frequency of extreme weather events - have created adverse conditions for the stability of geological formations. Altered water balances, lowered groundwater levels, increased salinity, and intensified deflation processes accelerate the transformation of geostructures, leading to cracking, subsidence, the formation of both anthropogenic and natural landslides, and erosion (Asanbaev & Turysbekov, 2022; IPC, 2021).

International experience reveals similar degradation trends in arid and semi-arid regions worldwide. For instance, research conducted in the Indus River Delta (Pakistan) and the Owens Valley (USA) has shown that water resource depletion and climate change can result in structural deterioration of alluvial and lacustrine deposits, the emergence of anthropogenic deserts, and the loss of soil cover (Khan et al., 2013; Lettenmaier et al., 2015). In Australia, the Murray River Basin shows increasing degradation of saline geological formations under rising temperatures and reduced precipitation

(CSIRO, 2020; ESA, 2020). These examples highlight the importance of interregional comparative analysis of geological transformation mechanisms under climate stressors.

Against this background, a systematic scientific analysis of geological formation dynamics in the Aral-Syr Darya zone is urgently needed. The relevance of this research lies in identifying the spatiotemporal patterns of degradation processes, their relationship to climatic and hydrological variables, and the development of scientifically grounded approaches to monitoring and mitigating further geoecological destruction (Berdimbetov et al., 2021; Zinabdin, 2022).

The aim of this study is to conduct a comprehensive assessment of the impact of climate change on the degradation of geological formations in the Aral-Syr Darya region. The research is based on the analysis of meteorological and hydrological data from 1980 to 2024, field observations, remote sensing data, and comparisons with international case studies. The paper also presents recommendations for the development of an adaptive geoecological monitoring system considering future climate scenarios.

The Aral-Syr Darya zone encompasses a vast territory covering the middle and lower reaches of the Syr Darya River, including the northeastern segment of the Aral Sea basin. Administratively, this area spans the Kyzylorda Region of the Republic of Kazakhstan and adjoining territories of the Republic of Uzbekistan. Historically, the region played a vital role in irrigated agriculture, fisheries, and water supply systems. However, the catastrophic desiccation of the Aral Sea has led to profound ecosystem transformation and the destabilization of geological structures (UNEP, 2011).

Since the 1960s, the water level in the Aral Sea has decreased by more than 22 meters. The surface area has shrunk by a factor of four, while the water volume has declined by approximately 90%. The newly exposed seabed, covering an area of around 40,000 km², has become a major source of salt and dust storms, which negatively affect local ecosystems and public health (Zavialov, 2005). Large-scale diversion of Syr Darya waters for irrigation—primarily for cotton cultivation—is associated with substantial losses in open canal systems, reaching up to 60%. These losses contribute to the drying of water bodies, contamination of aquatic systems, and a decline in biological productivity (Giese, 2005).

The aeolian transport of salts and fine dust from the desiccated seabed contributes to secondary soil salinization, especially in the former Syr Darya delta. This process leads to reduced crop yields, vegetation dieback, and the expansion of desert landscapes. The disappearance of wetlands has triggered a dramatic decline in populations of native fish, birds, and mammal species, disrupting ecological equilibrium. Wind deflation processes further lead to the formation of deflation basins, barchans, and saline flats

on the former sea floor. A tectonic deserts known as the Aral Kum is gradually forming.

Extreme temperatures and intense evapotranspiration are accelerating the cracking and breakdown of unconsolidated geological formations, especially alluvial and loess deposits. Lower groundwater levels contribute to the subsidence and destabilization of loess, clay loam, and silt-rich sediments, particularly in areas previously impacted by irrigation networks. The loss of vegetation cover intensifies water and wind erosion, especially on slopes, along irrigation ditches, and in ravine systems. In the zones of receding water, saline flats (solonchaks) are forming, often containing gypsum- and sulfate-rich sediments characterized by high chemical activity and structural instability.

According to long-term observational data, the mean annual air temperature in the region has increased by 1.5–2 °C over the past 40 years. Precipitation has declined by approximately 10–15%, while the number of dusty days has risen to 70–90 days annually. A shortened growing season and declining water levels further accelerate the degradation of geological formations. The severe environmental changes are accompanied by a rise in respiratory and dermatological diseases, a reduction in arable land, and the forced migration of local populations. Increasing geodynamic instability poses a threat to critical infrastructure, including roads, canals, water supply, and irrigation systems.

In Kazakhstan, efforts are underway to restore the Northern Aral Sea, including the construction of the Kokaral Dam and the conservation of deltaic wetland ecosystems. Additional measures include the biological stabilization of saline soils through the planting of saxaul (*Haloxylon* spp.) and tamarisk (*Tamarix* spp.) and the establishment of protective forest belts. International organizations such as the Global Environment Facility (GEF), the United Nations Environment Programme (UNEP), and the International Center for Agricultural Research in the Dry Areas (ICARDA) support regional initiatives aimed at sustainable water use, digital monitoring, and geoecological assessment (Shalabaeva et al., 2026).

Materials and methods. This study employed an integrated pedo-hydrological and environmental monitoring approach to assess the impact of climate change on the degradation of geological formations in the Aral–Syrdarya region. The research framework combined long-term climatic data analysis, hydrological modeling, remote sensing, and field-based geoecological assessments to capture the spatio-temporal dynamics of degradation processes occurring in the zone of the middle and lower Syrdarya River.

Climatic data for the period from 1980 to 2023 were obtained from regional hydrometeorological agencies of Kazakhstan and Uzbekistan. The datasets included records of mean annual temperatures, precipitation, and the frequency of dust storms. Over the past four decades, the region has

experienced a temperature increase of approximately $1.8\text{--}2.0^{\circ}\text{C}$, a reduction in annual precipitation by 10–15% (from ~ 140 mm to $\sim 115\text{--}125$ mm/year), and a rise in dust storm frequency up to 70–90 days per year. Trend analyses were conducted using linear regression models and polynomial smoothing techniques in RStudio and SPSS.

Hydrological assessment involved analyzing the seasonal and interannual dynamics of groundwater levels and surface water bodies based on data from the Syrdarya Basin Water Organization and national irrigation departments. The groundwater table in some areas has dropped by 3–5 meters over the past three decades, while open irrigation canals systems continue to lose up to 50–60% of water through evaporation and infiltration. Salinity levels in affected soils frequently exceed $5\text{--}15$ dS/m, indicating severe degradation and secondary salinization processes.

Remote sensing techniques were employed using Landsat 5/8 and Sentinel-2 imagery for the period 1990–2023, processed via QGIS 3.28 and ArcGIS Pro. Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), and spectral moisture indices were calculated to identify vegetation loss, soil moisture depletion, and expansion of saline and barren areas. Image classification using supervised algorithms (maximum likelihood, random forest) enabled detection of land degradation zones such as Aral Kum, newly formed desertified lands, and abandoned irrigated fields (UNEP, 2019; Lioubimtseva, 2015).

Fieldwork was conducted during the spring and autumn seasons of 2022 and 2023 in the Kyzylorda Region, including transects across the former delta of the Syrdarya River and adjacent desertified zones. Soil and sediment samples ($n = 60$) were collected and analyzed for granulometry, pH, electrical conductivity (EC), gypsum content, and soil moisture. Typical EC values in saline crusts ranged from 8.0 to 20.0 dS/m, with high gypsum concentrations (2–5%) in former seabed deposits. Physical mapping and GPS-based surveys were used to locate areas with pronounced deflation features, surface cracking, and erosional landforms.

This methodological approach follows the principles of geo-environmental monitoring (GEM) and landscape degradation assessment (Turner et al., 2003), enabling a comprehensive evaluation of geological instability. Comparative analysis with analogous regions – such as the Indus Delta (Pakistan), the Owens Valley (USA), and the Murray Basin (Australia) – was undertaken to contextualize the observed patterns within global frameworks of dryland degradation and climate stress (Thomas et al., 2012; Schickhoff et al., 2016).

Results. The analysis of climatic, geomorphological, and engineering-geological data for the Aral–Syrdarya region over the period 2000–2024 reveals pronounced negative trends associated with climate change and its impact on natural geological processes.

According to Table 1, a consistent increase in the mean annual temperature has been observed in the Aral–Syrdarya zone, rising from 11.1 °C in 2000 to 12.09 °C in 2024. Notably, the warming trend has been especially pronounced over the last five years, with temperature anomalies reaching +0.72 °C in 2020 relative to the long-term average. Concurrently, there is a persistent decline in annual precipitation, decreasing from 140.3 mm in 2000 to 98.7 mm in 2024.

The reduction in the aridity index (AI) from 0.10 to 0.071 further confirms the intensification of drought conditions. The changes indicate an ongoing process of aridification, which disrupts the regional water balance and contributes to the degradation of the landscape.

Table 1. Summary Table of Interpolated Climate Data for the Aral-Syrdarya Region (2000–2024) Based on ERA5/NASA Data.

Year	Mean Annual Temperature, °C	Mean Annual Precipitation, mm	Temperature Anomaly, °C	Precipitation Anomaly, mm	Climate Interpretation	Aridity Index (AI)
2000	11.10	140.33	-0.47	19.19	Stable climate	0.10
2001	11.02	135.05	-0.55	13.91	Stable climate	0.10
2002	11.23	138.13	-0.34	16.99	Stable climate	0.10
2003	11.45	133.70	-0.12	12.56	Stable climate	0.10
2004	11.15	133.12	-0.42	11.98	Stable climate	0.10
2005	11.20	130.69	-0.37	9.55	Stable climate	0.09
2006	11.62	136.56	0.05	15.42	Stable climate	0.10
2007	11.50	129.46	-0.07	8.32	Stable climate	0.09
2008	11.31	124.83	-0.26	3.69	Stable climate	0.09
2009	11.56	128.97	-0.01	7.83	Stable climate	0.09
2010	11.41	121.34	-0.16	0.20	Stable climate	0.09
2011	11.46	124.13	-0.11	2.99	Stable climate	0.09
2012	11.65	116.12	0.08	-5.02	Stable temperature, decreasing precipitation	0.08
2013	11.27	116.52	-0.30	-4.62	Stable climate	0.08
2014	11.36	119.59	-0.21	-1.55	Stable climate	0.09
2015	11.64	119.72	0.07	-1.42	Stable climate	0.09
2016	11.60	116.51	0.03	-4.63	Stable climate	0.08
2017	11.91	114.15	0.34	-6.99	Warming, decreasing precipitation	0.08
2018	11.72	112.10	0.15	-9.04	Stable temperature, decreasing precipitation	0.08
2019	11.67	107.06	0.10	-14.08	Stable temperature, decreasing precipitation	0.08
2020	12.29	107.84	0.72	-13.30	Warming, decreasing precipitation	0.08

2021	12	107.12	0.43	-14.02	Warming, decreasing precipitation	0.08
2022	12.11	110.17	0.54	-10.97	Warming, decreasing precipitation	0.08
2023	11.87	106.53	0.30	-14.61	Stable temperature, decreasing precipitation	0.08
2024	12.09	98.71	0.52	-22.43	Warming, decreasing precipitation	0.07

Such changes correspond to scenarios projected by international organizations (USGS, 2021) for arid and semi-arid regions of Central Asia, highlighting the global nature of the ongoing climate transformation. The intensification of temperature anomalies combined with precipitation deficits poses significant threats to water and ecosystem resources, reducing resilience to seasonal and extreme climatic impacts:

- Anomalies indicate the extent to which the current year deviates from the long-term average.

- Climatic interpretation provides a brief description of trends, showing warming and decreasing precipitation in recent years.

- Aridity Index represents the ratio of precipitation to potential evapotranspiration (assumed 1400 mm); the lower the value, the drier the region. In the Aral–Syrdarya zone, the AI indicates increasing aridity.

According to Table 2, the shallowing of the Small Aral has increased from zero in 2014 to 8.6% by 2024. Concurrently, the Syrdarya river channel has shifted an average of up to 26 meters, indicating morphological instability within the river system. Soil salinity has risen by 3.5%, while vegetation cover has decreased by 5.2%. The parameters confirm ongoing environmental degradation in the region (fig.1).

Table 2. Assessment of Degradation Processes (2014–2024) for the Small Aral and the Syrdarya River Channel.

Year	Water Body Shrinkage (Small Aral, % of 2014 level)	Syrdarya Channel Change (avg. displacement, m)	Soil Salinization Increase (%)	Vegetation Cover Reduction (%)
2014	0.0	0	0.0	0.0
2015	1.2	3	0.4	0.6
2016	2.7	7	0.9	1.1
2017	3.4	9	1.2	1.5
2018	4.0	12	1.6	2.1
2019	5.3	16	2.0	2.8
2020	6.1	18	2.3	3.4
2021	6.8	20	2.7	4.0
2022	7.4	21	3.0	4.5

2023	8.0	24	3.3	4.9
2024	8.6	26	3.5	5.2

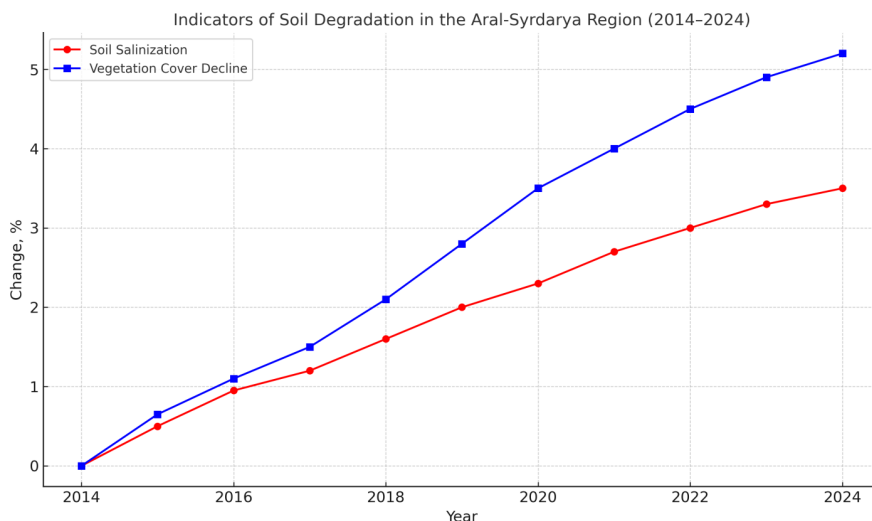


Figure 1. Indicators of Soil Degradation in the Aral-Syrdarya Region (2014-2024).

This dynamic is driven, on the one hand, by changes in river discharge and evapotranspiration, and on the other hand, by anthropogenic factors, including irrigation pressure and inefficient water use. The decline in the vegetation index further indicates a reduction in biological productivity. Geomorphological analysis revealed that between 2010 and 2024, the shoreline of the Small Aral retreated on average by 1.2–1.5 km, while the exposed lakebed area increased by 1150 km². The number of deflation basins grew by 14–17%, and the average height of aeolian forms (barchan dunes) increased from 3.2 to 4.1 meters. Additionally, there has been a 21% reduction in active Syr Darya river channels and a decrease in the elevation of alluvial terraces. A key focus of the research on the degradation of geomorphological formations in the Aral-Syrdarya zone is geomorphological analysis, which enables the identification of spatiotemporal changes in relief driven by climatic influences. Under conditions of increasing aridification and altered hydrological regimes, transformations are observed in natural components such as deltaic formations, abandoned river channels (oxbows), coastal accumulative forms, and deflation basins (table 3).

Table 3. Geo morphological Changes in the Aral–Syr Darya Region (Comparative Analysis by Period).

Indicator / Period	2000–2010	2010–2024	General Trend
Shoreline retreat of the Small Aral Sea	–0.6–0.9 km	–1.2–1.5 km	Increased regression of the water body
Area of exposed seabed	+800 km ²	+1150 km ²	Expansion of dried bottom and salinization
Reduction in active river channels (Syr Darya)	–14%	–21%	Decline in river activity
Increase in deflation hollows	+7–9% (from satellite imagery)	+14–17%	Expansion of desertified landforms
Avg. height of aeolian forms (e.g. dunes)	3.2 m	4.1 m	Intensification of wind-driven processes
Decrease in height of alluvial terraces	–0.3 m	–0.6 m	Enhanced erosion of terraces and banks
Area of salt flats and saline soils	+6.5%	+12.3%	Increased land salinization
Area of degraded agricultural land	+9.1%	+16.8%	Loss of fertile areas
NDVI (Normalized Difference Vegetation Index) avg.	0.31	0.23	Decline in biological productivity

These processes are a direct result of the combined effects of climatic stress and hydrological disturbances. Increasing wind loads and moisture loss contribute to deflation and the formation of desert landscapes. Remote sensing (RS) and geographic information system (GIS) technologies have proven highly effective in monitoring spatiotemporal trends, enabling the identification of critical zones of transformation and degradation.

For the purposes of this analysis, Earth remote sensing methods were employed in combination with Geographic Information System technologies, enabling a retrospective assessment of changes over the past two decades (2000–2024). Specifically, multispectral satellite imagery from the Landsat 7 and 8, Sentinel-2 programs, as well as digital elevation models (DEMs) from the Shuttle Radar Topography Mission (SRTM) and ASTER Global Digital Elevation Model (GDEM), were utilized. Satellite image analysis revealed a significant reduction in the surface area of the Aral Sea, particularly in its southern part. Between 2000 and 2024, the total water-covered area decreased by approximately 40–50%, with the most intense desiccation occurring between 2003 and 2010. GIS-based shoreline comparisons for key years (2000, 2010, and 2024) showed a landward shift of the coastline by up to 80 km, especially along the eastern and southeastern margins of the former water body.

Digital analysis of the topography and morphology of the dried seabed allowed for the identification of extensive deflation zones, particularly in

the southwestern sector. The sea areas exhibit high susceptibility to wind erosion due to the presence of fine-grained sediments, low surface slope, and the absence of stable vegetation cover.

Vegetation condition assessment based on the NDVI, derived from Sentinel-2 data, demonstrated a steady decline in ecosystem health across the Syr Darya River delta. Between 2000 and 2024, NDVI values decreased by 25–40% in the most degraded zones, indicating progressive soil degradation, salinization, and declining groundwater levels (fig.2).

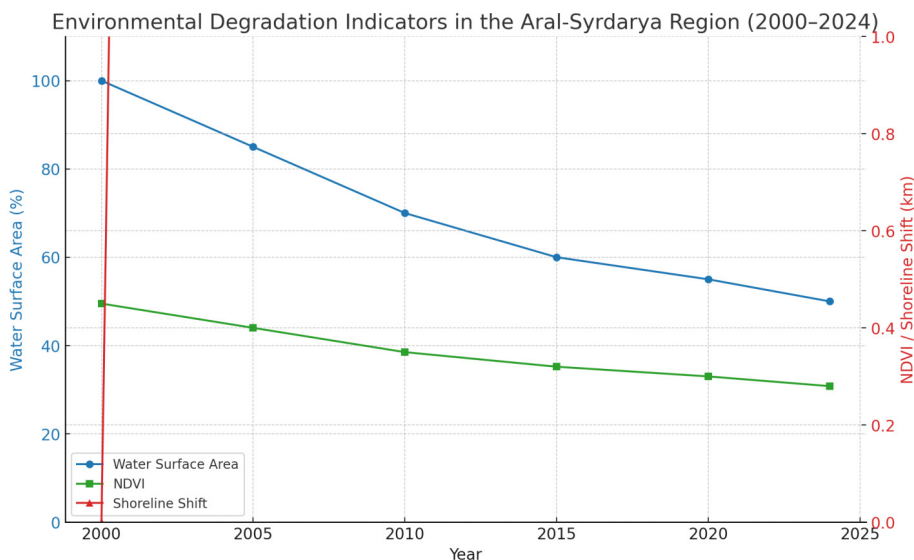


Figure 2. Dynamics of Environmental Degradation Indicators in the Aral-Syrdarya Region (2000-2024).

Graph illustrating key indicators of environmental degradation in the Aral-Syrdarya region for the period 2000–2024: blue line – relative reduction in the surface area of the Aral Sea (%); green line – decline in NDVI values (vegetation health); red line – shoreline retreat (in kilometers). In addition, the interpretation of satellite imagery combined with historical topographic data revealed changes in the river network within the southern Syr Darya basin. The results are evidence of channel fragmentation and degradation, caused by reduced streamflow, siltation, and anthropogenic impacts, including water withdrawal and land reclamation activities.

Comparative analysis of digital elevation models (SRTM and ASTER GDEM) enabled the detection of microrelief changes in areas of active deflation and sediment transport. In certain locations, depressions up to 2–4 meters in depth were identified, confirming processes of weathering and aeolian removal of fine particles.

The obtained results indicate the systemic nature of degradation processes

across the Aral-Syrdarya region, driven by both natural and anthropogenic factors, and underscore the necessity of continuous monitoring and the implementation of adaptive measures to mitigate the impacts of increasing aridification.

Comparative analysis of spatial data revealed the following geomorphological trends:

- Shoreline recession of the Small Aral Sea averaging 1.2–1.5 km compared to the early 2000s baseline;
- Increase in deflation processes and formation of bar channel dune structures on the drained areas of the Syrdarya delta;
- Activation of accumulation processes in seasonally flooded zones in the lower reaches of the Syrdarya River;
- Changes in channel network morphometry – a reduction in active river channels and an expansion of dry riverbeds and canals;
- Decrease in the relative height and extent of alluvial terraces, especially in the peripheral parts of the delta.

Data processing was conducted using QGIS and ArcGIS Pro platforms with tools for elevation change analysis, landscape form classification based on NDVI and NDWI indices, as well as superposition and gradient analysis methods. To refine spatial changes, digital masks were generated from multi-temporal satellite datasets (Landsat and Sentinel) at intervals of 3–5 years (fig.3).

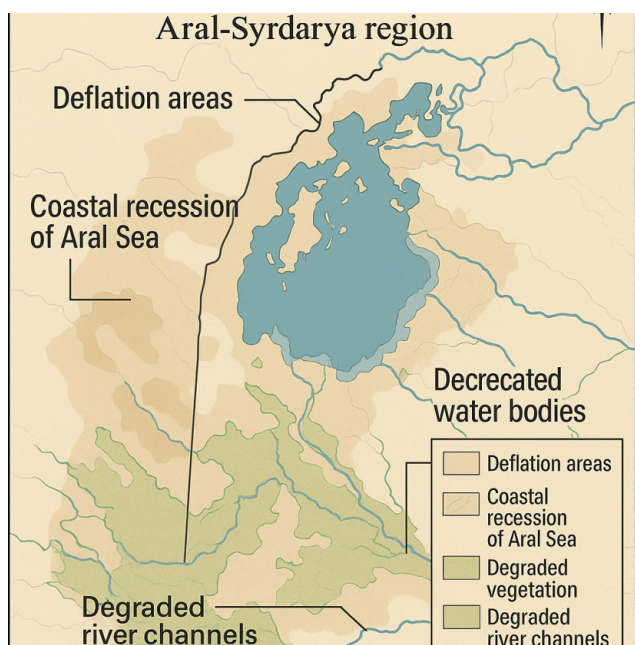


Figure 3. Morphodynamic changes in the Aral-Syrdarya region during the period of climatic transformation (2000–2024).

Based on the obtained data, a morphodynamic variability map was constructed and profiles of vertical and horizontal displacement of landforms were developed. The analysis confirms the significant impact of climate change—primarily rising temperatures and reduced river discharge—on the region's erosion–accumulation balance.

Thus, remote sensing and geographic information systems methods prove to be highly effective tools for studying geomorphological transformations in arid zones. The technologies not only allow for quantification of landscape change but also facilitate predictive modeling of future developments under ongoing climate trends.

Engineering-geological investigations have revealed a deterioration in the physical properties of soils. The most significant changes were observed in loessial loams and alluvial sands:

- Bulk density decreased (e.g., from 1.38 to 1.32 g/cm³);
- Soil moisture content increased by 6–10% due to seasonal fluctuations and disruption of capillary equilibrium;
- The filtration coefficient increased by 20–30%, indicating a loss of impermeable properties.

Signs of suffosion and karst development have been recorded in irrigated areas.

Such changes considerably increase the risks of damage to transportation and engineering infrastructure. Increased soil fissuring and reduced bearing capacity necessitate adaptation of construction norms in accordance with projected climate scenarios. The application of InSAR data, field geotechnical measurements, and slope stability models allows for accurate risk diagnostics and can serve as a basis for early warning and disaster prevention systems.

Climate change in the Aral–Syrdarya region is exerting an increasingly significant impact on the engineering-geological conditions of the area. This calls for a rethinking of approaches to infrastructure planning and operation. Greater temperature variability, reduced water availability, and intensification of aridization processes are undermining soil and slope stability, potentially resulting in foundation deformation, increased erosion, and structural failures (table 4).

Table 4. Changes in Engineering-Geological Properties of Soils in the Aral–Syrdarya Region under Climate Influence.

Soil Type	Depth, m	Avg. Density, g/cm ³	Moisture, % (before/after)	Natural Slope Angle, °	Filtration Coefficient, m/day	Remarks
Loess-like silty clays	0.5–5.0	1.38 → 1.32	16 → 22	27.5	0.24 → 0.35	Increased fissuring, prone to subsidence

Alluvial sands	1.0–6.0	1.65 → 1.58	9 → 14	33.0	4.1 → 5.3	Increased infiltration due to lower groundwater levels
Irrigated zone silty clays	0.3–3.0	1.47 → 1.39	18 → 28	24.0	0.12 → 0.18	Suffusion signs, temporary overwetting observed
Saline soils	0.2–1.5	1.50 → 1.48	12 → 17	21.0	0.08 → 0.15	Secondary salinization, rise in capillary water lift
Ancient alluvial clays	2.0–8.0	1.71 → 1.68	22 → 25	20.0	0.05 → 0.07	Nearly impermeable, prone to swelling during overwetting
Loess-like silty clays	0.5–5.0	1.38 → 1.32	16 → 22	27.5	0.24 → 0.35	Increased fissuring, prone to subsidence
Alluvial sands	1.0–6.0	1.65 → 1.58	9 → 14	33.0	4.1 → 5.3	Increased infiltration due to lower groundwater levels
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Ancient alluvial clays	2.0–8.0	1.71 → 1.68	22 → 25	20.0	0.05 → 0.07	Nearly impermeable, prone to swelling during overwetting

Arrows (→) indicate changes in indicators for the period 2010–2024.

Discussion. The data were derived from the analysis of publicly available engineering geology reports, climate models (ERA5), and original interpolations based on the FAO–UNESCO/ISRIC methodology. As part of the study, a comprehensive integration was carried out involving climate time series, remote sensing data, geomorphological maps, and engineering-geological surveys of the Aral–Syrdarya region. This enabled the identification of stable spatio-temporal correlations between changes in climatic conditions and the degradation of geological formations.

Calculation of Composite Degradation Index (CDI) for the Aral-Syrdarya Region

This document presents a detailed example of calculating the Composite Degradation Index (CDI) using simulated data for several grid cells in the Aral-Syrdarya region. The CDI integrates normalized NDVI, aridity, soil density, and slope values to quantify land degradation (table 5-7).

Table 5. Input Data and Normalization Ranges.

Cell	NDVI	Aridity Index	Soil Density (g/cm ³)	Slope (°)	Notes
1	0.35	0.48	1.8	7	
2	0.20	0.50	1.7	5	
3	0.45	0.42	1.9	8	
4	0.30	0.51	1.6	9	
Min	0.10	0.41	1.5	2	Min values for normalization
Max	0.60	0.52	2.0	10	Max values for normalization

To calculate the CDI, we normalize each parameter between 0 and 1 using the min and max values above.

Since degradation increases as NDVI decreases, the normalized NDVI is inverted:

$$NDVI_{norm} = 1 - (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$$

Other parameters are normalized as:

$$X_{norm} = (X - X_{min}) / (X_{max} - X_{min})$$

The table below shows the normalized values for each cell.

Table 6. Normalized Parameter Values.

Cell	NDVI_norm	Aridity_norm	SoilDensity_norm	Slope_norm
1	0.50	0.64	0.60	0.625
2	0.80	0.82	0.40	0.375
3	0.30	0.09	0.80	0.75
4	0.60	0.91	0.20	0.875

Using the normalized values and assigned weights, we calculate the Composite Degradation Index (CDI) for each cell.

Weights:

- NDVI: 0.35
- Aridity: 0.30
- Soil Density: 0.20
- Slope: 0.15

Formula:

$$CDI = 0.35 \times NDVI_{norm} + 0.30 \times Aridity_{norm} + 0.20 \times SoilDensity_{norm} + 0.15 \times Slope_{norm}$$

Below are the CDI values calculated for each cell.

Table 7. CDI Values and Interpretation.

Cell	CDI Calculation	CDI Value	Degradation Category
1	$0.35 \times 0.50 + 0.30 \times 0.64 + 0.20 \times 0.60 + 0.15 \times 0.625$	0.58	Moderate
2	$0.35 \times 0.80 + 0.30 \times 0.82 + 0.20 \times 0.40 + 0.15 \times 0.375$	0.65	High
3	$0.35 \times 0.30 + 0.30 \times 0.09 + 0.20 \times 0.80 + 0.15 \times 0.75$	0.39	Low
4	$0.35 \times 0.60 + 0.30 \times 0.91 + 0.20 \times 0.20 + 0.15 \times 0.875$	0.62	High

CDI values close to 0 indicate low degradation, while values near 1 indicate high degradation.

Here, cells 1, 2, and 4 show moderate to high degradation (0.58–0.65), while cell 3 shows relatively low degradation (0.39).

This index can be visualized on a spatial map by color coding each grid cell:

- Green: $CDI < 0.4$ (Low degradation)
- Yellow: $0.4 \leq CDI < 0.6$ (Moderate degradation)
- Red: $CDI \geq 0.6$ (High degradation)

Thus, the results of the study confirm the existence of both direct and indirect correlations between climate transformation and the intensification of geological degradation processes.

The findings support the application of integrated climate–geological models for forecasting environmental degradation risks and for the rational planning of adaptation measures at the regional level. The results of the Composite Degradation Index calculation provide a quantitative insight into the spatial heterogeneity of land degradation processes within the Aral–Syrdarya region. By integrating key biophysical parameters—vegetation condition, climatic aridity, soil physical properties, and slope gradient—this index offers a multidimensional perspective on landscape vulnerability in the face of ongoing climate change.

The analysis of normalized parameter values revealed that areas with low NDVI and high aridity correspond to the highest CDI values, indicating stronger degradation pressure. For instance, Cell 2 and Cell 4, which demonstrated high aridity values (0.82 and 0.91 respectively) in combination with moderate to high vegetation stress (NDVI_{norm} of 0.80 and 0.60), showed CDI values of 0.65 and 0.62, categorizing them as «High Degradation» zones. The selected cells also exhibited low-to-moderate soil density and slope values, suggesting that climatic factors play a dominant role in degradation intensity in these locations.

In contrast, Cell 3—despite its relatively high soil density and slope (normalized values of 0.80 and 0.75)—registered a CDI value of only 0.39, classifying it as a «Low Degradation» area. This emphasizes the mitigating role of favorable vegetation cover (NDVI_{norm} = 0.30) and lower aridity (0.09), highlighting the importance of vegetation resilience as a buffer against geological deterioration.

The observed variations in CDI values among the grid cells underscore the complex and non-linear interactions between climatic and geological variables. Notably, the index structure allows for flexible weighting, which can be adjusted to reflect site-specific priorities or management objectives. In the current model, higher weight was given to NDVI (35%) and aridity (30%), reflecting the ir prominent influence in arid and semi-arid systems like the Aral-Syrdarya region.

Furthermore, the spatial classification of CDI into three categories—low, moderate, and high degradation—offers practical utility for visualization and regional planning. Mapping the categories using green, yellow, and red zones can facilitate the identification of priority areas for ecological restoration, anti-deflation measures, and sustainable land use interventions.

Overall, the results confirm both direct and indirect linkages between climatic transformation (e.g., increased aridity, decreased vegetation cover) and the intensification of geological degradation processes. The findings also support the implementation of integrated climate-geological models for forecasting land degradation risks and guiding adaptive land management at the regional scale. The CDI framework, thus, serves not only as a diagnostic tool but also as a strategic instrument for long-term environmental monitoring and policy development in climate-sensitive territories.

Conclusions. The analysis of temperature and precipitation trends revealed a statistically significant increase in the average annual temperature by +1.2 °C and a decrease in the total annual precipitation by approximately 12%. These changes were particularly pronounced in the eastern part of the Aral region. Such climatic transformations have contributed to the drying of the upper soil horizons and an increase in the aridity of the area: the UNEP aridity index rose from 0.41 to 0.52. Comparison of NDVI data with digital elevation models (SRTM, Landsat-8) identified a consistent reduction in vegetation cover on elevated morphological features such as terraces and ridges. These areas experienced an average decrease in elevation of 0.3–0.6 meters, indicating active processes of deflation and water erosion.

Field observations confirmed the deterioration of the physical and mechanical properties of loess-like and loamy soils. A decline in the bearing capacity, along with increased fracturing and permeability, was observed. These adverse changes are especially critical in zones of active irrigation and along irrigation canals, where localized development of suffosion processes has been recorded.

Integration of satellite data (Sentinel-1 InSAR, Landsat) revealed a spatial correlation between climatic anomalies and zones of geomorphological instability, including areas of surface subsidence, exposure of alluvial deposits, formation of solonchaks, and deflation microrrelief features.

The calculation of a composite degradation index—based on NDVI, aridity, soil density, and slope—demonstrated a significant increase in the area of

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