

FEATURES OF THE FORMATION AND DYNAMICS OF LANDSCAPE-ECOLOGICAL CONDITIONS IN THE COASTAL GEOSYSTEMS OF THE CASPIAN SEA (A CASE STUDY OF THE SAMUR-DAVACHI LOWLAND)

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Keywords: Samur-Davachi lowland, Caspian Sea coast, transgression, regression, aqual landscapes

Summary. This study investigates the spatio-temporal dynamics, structural transformation, and ecological stability of coastal landscapes across the Samur-Davachi lowland under the dual influence of Caspian Sea level fluctuations and anthropogenic activities. Integrating multi-decadal sea-level records, field landscape mapping, and hydrogeological data, we evaluate landscape response across transgressive (1978–1995) and subsequent regressive (post-1995, below -29.0 m) phases. Results indicate that during peak transgression, marine waters inundated 80–100 km² of coastal semi-desert, forcing shorelines inland by 200–300 m in the north, up to 1500 m in the south, and 4–5 km in the Agzybir lagoon sector, re-establishing the historical 1926 baseline. Rising groundwater tables induced three distinct waterlogging tiers: severely (0.0–0.5 m depth), moderately (0.5–1.5 m depth), and weakly (1.5–3.5 m depth) waterlogged geosystems, driving widespread transition into subaqueous aqual and wetland complexes. On the Shollar plain, century-long anthropogenic pressure reduced forest cover by 2.0–2.5 times, leaving 60–65% as secondary stands and accelerating forest steppification. Crucially, increased soil hydromorphy accelerated vegetation colonization on coastal dunes, dampening aeolian mobility and stabilizing psammomorphic systems. These findings highlight the non-linear coupling of natural and anthropogenic drivers and emphasize the necessity of adaptive land-use strategies along dynamic Caspian coastal zones.

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Introduction

The Caspian Sea the largest enclosed inland body of water on Earth and its surrounding coastal environments function as an integrated natural complex (Kostianoy & Kosarev, 2005). Characterized as a highly complex, multifunctional, and self-regulating geosystem, this unique environment exists in a dynamic equilibrium that can either accommodate sustainable human activity or suffer catastrophic degradation from uncoordinated and intensive anthropogenic pressure (Lattuada et al., 2019). The structural origin, ongoing functionality, and evolutionary trajectories of these coastal landscapes are fundamentally governed by the natural periodic and cyclical oscillations of the Caspian Sea level.

In recent decades, the compounding impacts of falling Caspian Sea levels and escalating regional land use have given rise to intricate, stressed landscape-ecological conditions (Ismayilov et al., 2023; Lahijani et al. 2023]. A prime example of this environmental vulnerability is observed in the Samur-Davachi lowland (located along the northwestern coast of the Caspian Sea in northern Azerbaijan). This accumulative lowland plain, serves as a vital ecological corridor containing forest ecosystems (Ismayilov & Jabrayilov, 2019).

Understanding the mechanisms driving the formation and temporal dynamics of landscape-ecological conditions within the Samur-Davachi lowland is crucial for both environmental monitoring and sustainable land-use planning. Therefore, this study aims to evaluate the spatio-temporal evolution of coastal geosystems in the Samur-Davachi lowland, analyzing the complex interplay between Caspian Sea level variations, hydrological regime changes, soil-vegetation successions, and anthropogenic influences.

Methods

To evaluate the spatio-temporal dynamics and ecological transformations of coastal landscapes across the Samur-Davachi lowland, this study integrated empirical field landscape mapping with historical and multi-source spatial datasets. Field surveys conducted along transect lines recorded local hydro-geomorphological parameters, plant community successions, soil profile characteristics (specifically depth to groundwater, soil moisture, and salinization markers), and coastal dune morphometrics. These field observations were synthesized with multi-decadal Caspian Sea level records (1926–present), long-term hydrogeological monitoring data, land-use/land-cover archival records, and multi-scale topographic and thematic maps. Spatial differentiation of landscape units was carried out using a factor-dynamic geosystem framework, categorizing coastal environments into distinct hazard tiers based on waterlogging severity (0.0–0.5 m, 0.5–1.5 m, and 1.5–3.5 m groundwater depths), substrate genesis, and structural resilience under transgressive and regressive marine phases.

Analysis and discussion

A multi-temporal analysis of the modern and long-term functional dynamics, directionality, and intensity of coastal landscape development reveals three primary driving factors:

1. *Hydro-climatic fluctuations*: Variations in the base level of the Caspian Sea, combined with broader regional changes in river discharge and basin runoff regimes across Azerbaijan (Makhmudov et al., 2025), dictate the fundamental spatial-temporal oscillations between hydromorphic (wetland) and xeromorphic (drier terrestrial) landscape states across the coastal strip.

2. *Neotectonic dynamics*: Tectonic movement and morphostructural variations across coastal lowlands generate localized differences in slope, subsidence, and uplift, thereby controlling the specific direction and rate of landscape evolution.

3. *Anthropogenic pressures*: Human land use introduces a complex layer of modification that interacts with natural cycles, particularly in heavily settled and farmed areas such as the Samur-Davachi lowland.

The interaction between natural environmental cycles and human activities creates complex operational dynamics within these coastal geosystems. This superimposition manifests primarily through two distinct mechanisms:

- *Synergistic amplification* (anthropogenic acceleration of natural trends): Human activities can accelerate natural degradative or evolutionary landscape processes. For instance, during phases of Caspian Sea level rise, natural waterlogging and coastal water table elevation across the Samur-Davachi lowland are further aggravated by intensive agricultural surface irrigation around rural settlements such as Valamir, Tikanlioba, and Barakhum. The cumulative effect of rising groundwater and over-irrigation induces secondary soil salinization and marsh formation.

- *Anthropogenic neutralization and buffer interventions*: Conversely, targeted structural engineering can partially suppress or counteract natural landscape trends. Within the Samur-Davachi lowland, human engineering works actively alter natural hydromorphic trajectories. The construction and operation of widespread collector-drainage networks serve as a buffer, mitigating excessive waterlogging, lowering saline water tables, and maintaining agricultural viability against coastal flooding and groundwater rising.

Changes in landscape-ecological conditions in relation to Caspian Sea level fluctuations.

One of the primary natural drivers influencing the dynamics of coastal lowland landscapes is the fluctuation of the Caspian Sea level (Duan et al., 2025). It contributes to alterations in the morphological structure of landscapes, increases the complexity of intra-landscape differentiation, and accelerates the intensity of other natural processes.

Long-term meteorological records along the Caspian littoral reveal complex multi-decadal cycles in moisture availability and thermal regimes. M.J. Ismayilov (1986) classified precipitation dynamics along the Caspian coast (1848–1980) into three major hydro-climatic phases: a relatively arid phase (1848–1902), a prolonged humid phase (1903–1952), and a subsequent dry phase beginning in 1953. In parallel, analysis of thermal dynamics by G.A. Hajiyevev (1975) distinguished two primary multi-decadal temperature epochs: a cooler period (1848–1910) during which mean temperatures remained 0.3°C below the long-term baseline, followed by a warmer period (1911–1972) with temperatures averaging 0.4°C above the prior epoch.

These climatic oscillations closely correspond to significant non-linear shifts in the hydrological base level of the Caspian Sea:

- **1882–1977 regressive phase**: A continuous decline in sea level resulting in a cumulative drop of 3.82 m [5].
- **1978–1995 transgressive phase**: A rapid sea-level rise of 2.8 m documented through continuous instrumental observations.

- **1995–present regressive phase:** A substantial level drop exceeding 3.0 m, which has significantly exposed littoral zones and restructured coastal wetland habitats (Fig. 1).
- **Recent morphological observations (Jan–Jul 2026):** Morphological assessment of coastal ecosystems during the first half of 2026 indicates a slight localized rise in sea level of 5–8 cm. Long-term instrumental monitoring remains necessary to determine whether this rebound signals a multi-year shift or a brief seasonal fluctuation.



Fig. 1. Exposed rocky formations resulting from sea-level regression (left) and diagenetic structures (right)

Crucially, the direct cause and effect relationship between regional precipitation/temperature anomalies and Caspian Sea level variations remains intricate and non-linear. Although the broader regional climate has remained relatively dry since the mid-20th century, the sea level has undergone two major, opposing multi-decadal oscillations during this same period. These base-level variations serve as the primary driver for ecological succession, triggering intense spatial differentiation, soil salinization/desiccation, and structural reorganization across both pristine natural habitats and human-modified agricultural landscapes.

Field investigations and office-based (analytical) studies revealed that the influence of sea-level draw-down on groundwater depth diminishes with increasing distance from the coastline. Specifically, during the study period, the zone of intensive groundwater table decline along the Samur-Davachi lowland coastal belt extended to a width of 0.5–1.0 km. Studies demonstrate that following 1929, over a 50-year period, the Caspian Sea retreated by nearly 4 km. As a result, vast areas of the Davachi lagoon and the shallow coastal shelf zone adjacent to the Samur-Davachi lowland transitioned to continental development conditions.

An analysis of climatic data reveals that during the period when the Caspian Sea level fell by 2.5 m, annual potential evapotranspiration in the coastal section of the Khachmaz district increased by 5–8% compared to the long-term baseline (1900–1930). The shrinking surface area of the Caspian Sea due to base-level regression intensified climatic continentality, which in turn accelerated desertification processes across the western Caspian coast and drove the replacement of degraded hygrophytic and mesophytic plant communities with xerophytic ones. Notably, the drop in Caspian Sea levels also directly impacts the biological productivity of coastal landscapes.

In connection with the retreat of the sea prior to 1977, the mineralization (salinity) of groundwater in the coastal depressions of the Samur-Davachi lowland gradually decreased. This reduction facilitated a vegetative succession from obligate halophytes (*Salicornia* and *Suaeda* species), through transitional plant groupings, to a meadow-solonchak plant complex dominated by *Salsola soda*, *Puccinellia* (alkali grass), *Petrosimonia*, and ephemeral species.

Starting in 1977, a rise in the level of the Caspian Sea took place, leading to an elevation of groundwater tables and an overall transformation of the ecological environment within natural-territorial complexes (NTCs). By 1998, the sea level had risen by more than 2.0 meters, after which a relative stabilization was observed. Consequently, over the past two decades, the operational trajectory and evolutionary direction of contemporary landscapes have fundamentally shifted.

The latter induces waterlogging/submersion. To define this phenomenon accurately: first, the target object of waterlogging must be clearly specified (e.g., the soil-substrate horizon, plant root systems, building foundations, etc.); second, the drivers causing the groundwater level rise are not included in the strict definition of waterlogging itself. From this, it follows that the waterlogging of an object occurs when that object, originally situated above the groundwater table (or above the capillary fringe) becomes fully or partially submerged in a groundwater-saturated medium as a result of a table rise (Kupriyanova & Trapeznikova, 1997).

Based on field landscape investigations, supplemented by published literature and archival records (including data on groundwater depths, natural landscape structure, land use patterns, and long-term Caspian Sea level dynamics), as well as topographic and thematic maps, coastal geosystems of the Samur-Davachi lowland were classified into distinct types according to the degree of transformation induced by the Caspian Sea:

1. Fundamentally transformed (submerged) geosystems;

2. Geosystems subject to varying degrees of waterlogging.

The first geosystem type encompasses narrow coastal strips of the Samur-Davachi lowland. Here, semi-desert landscapes predominantly occupy the immediate shoreline of the Caspian Sea, while across the territory of the Khachmaz and Siyazan districts, their boundaries gradually extend toward the central part of the lowland from northwest to southeast. The width of this landscape zone varies in response to local physical-geographic conditions.

From the southern tributaries of the Samur River southeastward to the settlement of Niyazoba, the semi-desert landscape in the coastal zone of the Caspian Sea occupies only a narrow strip, approximately 400–1200 m in width. In contrast, in the Siyazan area, its width reaches 3–4 km. Prior to the rise in Caspian Sea levels, younger and more dynamic landscapes were actively forming here.

Contemporary deposits along the coastal zone of the sea are primarily represented by sand and gravel, framing the coastline as a narrow strip (Anoikin et al., 2023). Gravel and pebbles are predominantly distributed along the coast of the Yalama and Mukhtadir areas. To the south, in the Khachmaz and Shabran districts, these are gradually replaced by sand along the littoral zone. Moving southward from the Samur River delta, the width of the highly dynamic and unstable beach complexes increases significantly. For instance, along the Yalama and Mukhtadir coasts, the width of the coastal semi-desert landscape varies between 100 and 1,200 meters, whereas in the Khachmaz and Shabran sectors, the shallow shelf waters extend to 3–4 kilometers in width. This condition has driven the formation of sandy ridges that constitute elementary landscape units.

In connection with the rise in the Caspian Sea level up to 1998, the semi-desert landscape shifted inland by 200–300 m in the northern part of the coast to 1000–1500 m in the southern part. The primary portion of this semi-desert landscape transitioned to a subaqueous development regime, transforming into aquatic landscapes. Even in the area of the Agzybir lagoon, the shoreline moved 4–5 km inland, reconstituting the historical shoreline position of 1926. According to our calculations, 80–100 km² of semi-desert landscape was inundated by marine waters.

Based on landscape characteristics, coastal aeolian (wind-formed) landforms can be divided into stabilized (anchored) and unstabilized (active/mobile) groups. Unstabilized or mobile sand-and-shell materials include coastal dune ridges extending along the shore from northwest to southeast. The relative height of these dunes ranges from 2–3 meters to 10–12 meters, reaching 15–17 meters above the Caspian Sea level in certain places.

Within the functional-dynamic structure of the coastal plain landscapes of the Samur-Davachi lowland, a purely natural component could not be isolated. The anthropogenic factor has become fully integrated within it, driving highly diverse trends in landscape evolution (Gu et al., 2022). On the aeolian-marine plain, overgrazing exacerbates landscape instability. On the Shollar plain, forests with a canopy density of 0.4–0.5 currently account for 75% of the forested area. The reduction in forest canopy density here is primarily linked to unmanaged logging, livestock grazing, and the spread of timber diseases. Over the past 100 years, the forest cover of the Shollar plain has decreased by a factor of 2 to 2.5; secondary forests now constitute 60–65% of the existing oak-hornbeam and ash-hornbeam forest complexes (Figure 2).

Conclusion

Natural and anthropogenic factors can be unidirectional, such as the mutual intensification of hydromorphy, thereby accelerating the overall process, which is currently taking place across many irrigation systems on the Caspian coast of the Samur-Davachi lowland. Conversely, when observed natural processes operate in multidirectional orientations, they tend to cushion, if not mitigate, the adverse consequences of human activities. Such is the natural process of dune ridge stabilization under conditions of increasing hydromorphy within the landscape waterlogging zone.

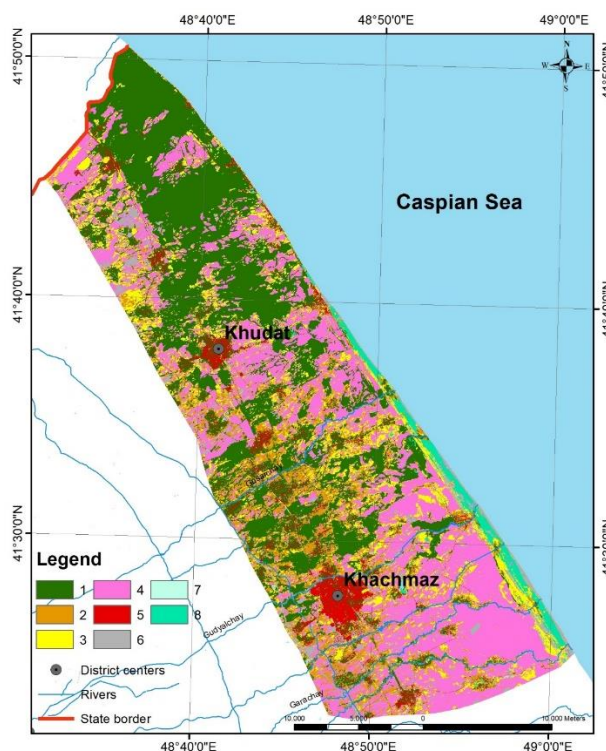


Fig. 2. Dynamics of transformation of forest cover on the Shollar plain from 1910 to 2025

Legend: 1. Existing oak-hornbeam forest ecosystems; 2. Deforested shrubby dry steppes affected by anthropogenic impacts; 3. Post-forest pasture-hayfield complex; 4. Post-forest agrolandscapes; 5. Rural and urban residential (seliteb) landscapes; 6. Coastal sandy and pebbly beach landscape; 7. Lakes (artificial reservoirs); 8. Coastal reedy and meadowy hydromorphic landscapes formed by the retreat of the sea.

Thus, an analysis of studies related to Caspian Sea level fluctuations demonstrates that a fully synchronous correlation between long-term dynamics of air temperature, atmospheric precipitation, and sea level oscillations is weakly observed. Over the past 50 years, during which dry and warm climatic periods were recorded, the sea level exhibited both a significant transgressive phase (1978–1995) and a subsequent regressive phase (from 1995 to the present). This situation necessitates more rigorous, comprehensive research into sea level fluctuations. Under these circumstances, prioritizing scientific investigations focused on the problems of human land-use adaptation to sea level oscillations becomes paramount.

As a result of Caspian Sea level fluctuations, the natural and economic structures of the coastal zone undergo substantial changes, though these are not always negative for human society. However, further unmitigated oscillations in the level of the Caspian Sea will drastically intensify negative impacts on economic activities across the Samur-Davachi Lowland.

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ОСОБЕННОСТИ ФОРМИРОВАНИЯ И ДИНАМИКИ ЛАНДШАФТНО-ЭКОЛОГИЧЕСКИХ УСЛОВИЙ ПРИБРЕЖНЫХ ГЕОСИСТЕМ КАСПИЙСКОГО МОРЯ (НА ПРИМЕРЕ САМУР-ДИВИЧИНСКОЙ НИЗМЕННОСТИ)

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Резюме. В исследовании рассматриваются пространственно-временная динамика, структурная трансформация и экологическая устойчивость прибрежных ландшафтов Самур-Дивичинской низменности в условиях совместного воздействия колебаний уровня Каспийского моря и антропогенной деятельности. На основе комплексного анализа многолетних данных об уровне моря, результатов полевого ландшафтного картографирования и гидрогеологических показателей оценена реакция ландшафтов на изменения природных условий в периоды трансгрессии (1978–1995 гг.) и последующей регрессии (после 1995 г., при снижении уровня моря ниже отметки –29,0 м). Установлено, что в период максимальной трансгрессии морские воды затопили 80–100 км² прибрежных полупустынных ландшафтов, вызвав смещение береговой линии вглубь суши на 200–300 м на севере, до 1500 м на юге и на 4–5 км в районе лагуны Агзыбир. В результате береговая линия вернулась к своему историческому положению, зафиксированному в 1926 г. Повышение уровня грунтовых вод обусловило формирование трёх категорий геосистем по степени переувлажнения: сильно переувлажнённых (глубина залегания грунтовых вод 0,0–0,5 м), умеренно переувлажнённых (0,5–1,5 м) и слабо переувлажнённых (1,5–3,5 м). Эти процессы способствовали масштабной трансформации прибрежных ландшафтов в субаквальные и водно-болотные комплексы. На Шолларской равнине в результате столетнего антропогенного воздействия площадь лесного покрова сократилась в 2,0–2,5 раза, при этом 60–65% сохранившихся лесных насаждений представлены вторичными древостоями, что сопровождалось активизацией процессов остепнения лесов. Вместе с тем усиление гидроморфизма почв способствовало ускоренному заселению прибрежных песчаных дюн растительностью, снижению интенсивности эоловых процессов и стабилизации псаммоморфных геосистем. Полученные результаты свидетельствуют о нелинейном характере взаимодействия природных и антропогенных факторов и подчёркивают необходимость разработки адаптивных стратегий землепользования в динамично изменяющихся прибрежных зонах Каспийского моря.

Ключевые слова: Самур-Девичинская низменность, побережье Каспийского моря, трансгрессия, регрессия, аквальные ландшафты

XƏZƏR DƏNİZİNİN SAHİL GEOSİSTEMLƏRİNDƏ LANDŞAFT-EKOLOJİ ŞƏRAİTİN FORMALAŞMASI VƏ DİNAMİKASININ XÜSUSİYYƏTLƏRİ (SAMUR-DƏVƏÇİ OVALIĞI TİMSALINDA)

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Xülasə. Tədqiqatda Xəzər dənizinin səviyyə tərəddüdləri və antropogen fəaliyyətin birgə təsiri şəraitində Samur-Dəvəçi ovalığının sahil landşaftlarının məkan-zaman dinamikası, struktur transformasiyası və ekoloji dayanıqlılığı araşdırılmışdır. Dəniz səviyyəsinin çoxillik müşahidə məlumatları, çöl landşaft xəritələşdirilməsinin nəticələri və hidrogeoloji göstəricilər kompleks şəkildə təhlil edilərək transqressiya (1978–1995-ci illər) və sonrakı reqressiya (1995-ci ildən sonra dəniz səviyyəsinin –29,0 m-dən aşağı enməsi)

mərhələlərində landşaftların dəyişikliklərə reaksiyası qiymətləndirilmişdir. Nəticələr göstərir ki, transqressiyanın maksimum mərhələsində dəniz suları sahilboyu yarımsəhra landşaftlarının 80–100 km² sahəsini basmış, sahil xəttinin şimalda 200–300 m, cənubda 1500 m-ə qədər, Ağzıbir laqunu ərazisində isə 4–5 km quruya doğru irəliləməsinə səbəb olmuşdur. Bununla da sahil xətti 1926-cı ildə qeydə alınmış tarixi vəziyyətinə qayıtmışdır. Qrunt sularının səviyyəsinin yüksəlməsi nəticəsində izafi rütubətlənmənin üç dərəcəsi fərqləndirilmişdir: güclü (qrunt sularının dərinliyi 0,0–0,5 m), orta (0,5–1,5 m) və zəif (1,5–3,5 m) izafi rütubətlənməyə məruz qalan geosistemlər. Bu proses sahil landşaftlarının geniş ərazilərdə sualtı akval və bataqlıq komplekslərinə transformasiyasını sürətləndirmişdir. Şollar düzənliyində bir əsr ərzində davam edən antropogen təzyiq nəticəsində meşə örtüyünün sahəsi 2,0–2,5 dəfə azalmış, mövcud meşəliklərin 60–65%-ni törəmə meşəliklər təşkil etmiş və meşələrin çölləşməsi prosesi intensivləşmişdir. Bununla yanaşı, torpaqların hidromorfluq dərəcəsinin artması sahilboyu qum təpələrində bitki örtüyünün formalaşmasını sürətləndirmiş, eol proseslərinin fəallığını zəiflətməmiş və psammomorf geosistemlərin sabitləşməsinə şərait yaratmışdır. Tədqiqatın nəticələri təbii və antropogen amillər arasındakı qeyri-xətti qarşılıqlı əlaqələri üzə çıxarır və Xəzər dənizinin dinamik sahil zonalarında torpaqdan istifadənin dəyişən təbii şəraitə uyğunlaşdırılmış strategiyalar əsasında təşkilinin zəruriliyini əsaslandırır.

Açar sözlər: Samur-Dəvəçi ovalığı, Xəzər dənizi sahili, transqressiya, reqressiya, akval landşaftlar