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CASPIAN SEA LEVEL DYNAMICS AND THE ECOLOGICAL RANSFORMATION OF COASTAL ECOSYSTEMS

Nagmanov D.G., Bauyrzhankyzy M.
LLP "Al-Farabi Operating", Aktau, Kazakhstan
e-mail: diasnagmanov@mail.ru, e-mail: Madina.bauyrzhankyzy@gmail.com

Annotation. This article presents a comprehensive analysis of the impact of Caspian Sea level changes on the condition of coastal ecosystems over the period 1980–2025. The study is based on a synthesis of long-term hydrometeorological observations, satellite remote sensing data, and the results of regional environmental studies. Long-term trends in sea-level fluctuations, changes in the hydrological balance, and the spatial dynamics of biodiversity along the Kazakh, Russian, and Turkmen coastal sectors were identified. The findings indicate that the average rate of Caspian Sea level decline is approximately 6.4 cm per year, resulting in the degradation of coastal and wetland ecosystems, a decrease in waterbird populations, shoreline transformation, and the loss of key spawning grounds for commercially important fish species. Potential changes in sea level and coastal ecosystems up to 2050 were projected using CMIP6 climate scenarios. Based on the findings, priority measures for adaptation, environmental management, and the establishment of a long-term monitoring system are proposed. The results of this study may be used in developing regional nature conservation strategies and promoting sustainable natural resource management under intensifying climate change in the region [1].

Keywords: Caspian Sea, sea level, coastal ecosystems, hydrological balance, climate change, environmental degradation, biodiversity, adaptation.

Introduction

Changes in the level of the Caspian Sea represent one of the most pressing environmental challenges in Eurasia. As the world's largest enclosed inland water body, the Caspian Sea has a significant influence on the climate, biodiversity, and economy of the surrounding regions. Another period of sea-level decline began in the early 1980s. According to data from the Shirshov Institute of Oceanology of the Russian Academy of Sciences and Kazhydromet, the sea level decreased by more than 2 m between 1980 and 2025. The main causes include increased evaporation resulting from rising temperatures, reduced river inflow, particularly from the Volga River, and anthropogenic regulation of the hydrological regime. The aim of this study is to assess the impact of these changes on coastal ecosystems, identify spatiotemporal patterns, and propose appropriate adaptation measures [2].

Research objectives:

- To analyse the dynamics of the Caspian Sea level over the period 1980–2025;
- To determine the relationships between climatic factors (temperature, precipitation, and evaporation) and sea-level fluctuations;
- To assess the effects of sea-level decline on biodiversity and the productivity of coastal ecosystems;
- To develop recommendations for adaptation and coastal zone management [8].

Research into Caspian Sea level fluctuations has been conducted since the nineteenth century, with its intensity increasing following the sea-level decline observed in the 1980s. The main contribution to sea-level dynamics is determined by the balance between river inflow and evaporation. Approximately 80% of the total river inflow is provided by the Volga River (Ivanov et al., 2021). An increase in mean annual temperatures in the region (+1.5–2 °C) has resulted in a 10–15% increase in evaporation (Nasyrova & Bekturganov, 2023). Anthropogenic factors, including

dams, reservoirs, river flow regulation, and hydrocarbon extraction, further intensify natural fluctuations (Aliyev, 2020; Kasperskaya et al., 2022). Projections based on CMIP6 scenarios indicate a further decline in sea level under current trends (Kostianoy et al., 2021).

Materials and Methods. Data sources. The study used hydrometeorological observation records from Kazhydromet and the Shirshov Institute of Oceanology of the Russian Academy of Sciences, as well as satellite remote sensing data from Landsat, Sentinel, and NASA Earth Observations.

Study period: 1980–2025.

Study areas: The Kazakh sector (Mangystau Region, the Kurayty area and Cape Peschany), the Volga River delta, and the Turkmen sector (the Turkmenbashi area).

Research methods: Time-series analysis using moving averages, water balance calculations, correlation analysis of temperature and sea-level data, biogeographical analysis of vegetation and avifauna, and climate scenario modelling based on CMIP6 [9, 10].

Hydrological analysis — smoothing equation:

$$H_t = \frac{1}{n}\sum_{i=1}^{n}(L_i - L_i - 1)$$

Water mass balance equation:

$$\Delta V = Qr - E + P - Qa$$

where:

- Qr — total river inflow;
- E — evaporation;
- P — precipitation;
- Qa — anthropogenic water withdrawal.

Predictive regression model:

$$H_f = aT + bP + cE + d$$

where:

- T — temperature change;
- P — precipitation change;
- E — evaporation change;
- a,b,c,d — empirical regression coefficients estimated from observational data.

Results and Discussion. Dynamics of Sea-Level Changes. The analysis of the 1980–2025 period demonstrates a persistent downward trend in the Caspian Sea level, with an average decline rate of 6.4 cm per year. This finding is consistent with Ivanov et al. (2021) and Kazhydromet data. Following a short-term rise during the 1990s, a sustained decline in sea level has been observed [6].

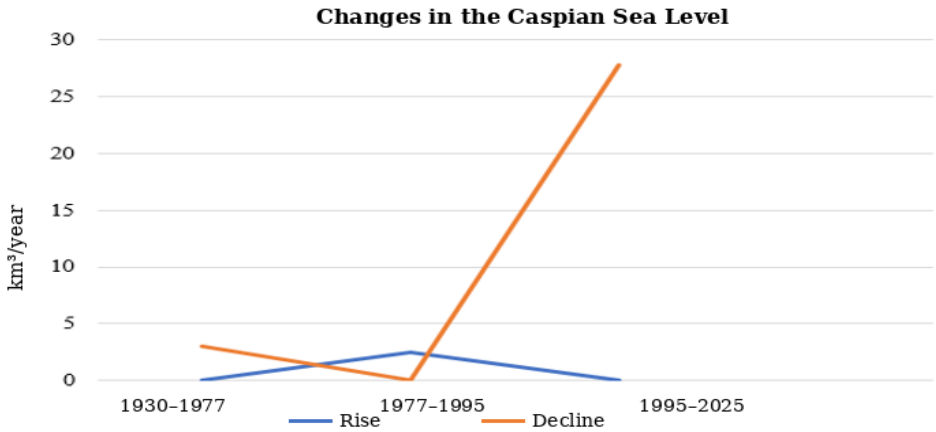


Figure 1. Dynamics of the Caspian Sea level during 1980–2025.

Correlation with Climatic Factors. The average correlation coefficient between air temperature and sea level was (r=-0.78), indicating a strong negative relationship. An increase in temperature is associated with a decrease in sea level, primarily due to enhanced evaporation.

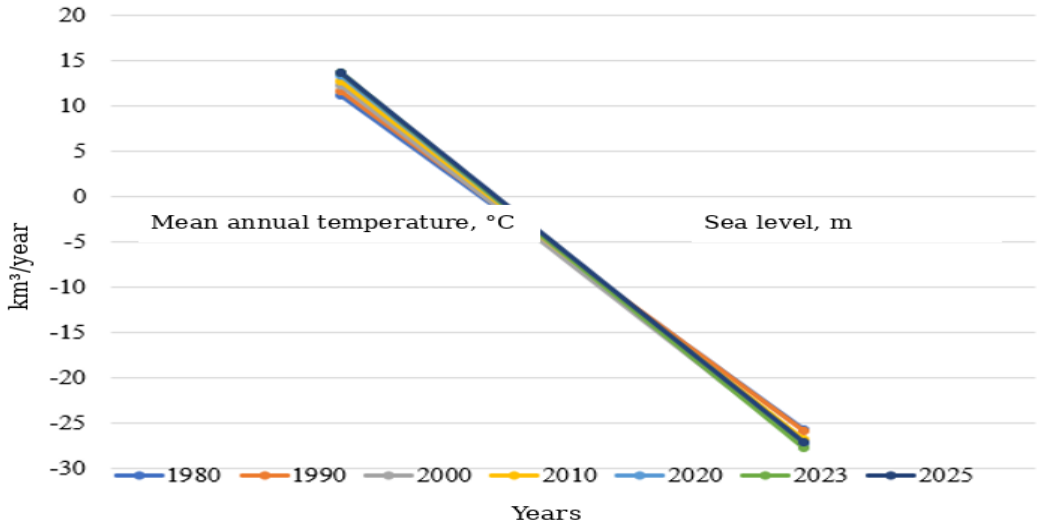


Figure 2. Correlation between mean annual air temperature and sea level (1980–2025).

Changes in the Hydrological Balance7 Calculations based on Equation (2) indicate that over the past decade, evaporation has increased by approximately 12%, while river inflow has decreased by approximately 8%. The average negative water balance is estimated at approximately −25 km³/year [3, 7].

Table 1. Water mass balance of the Caspian Sea (km³/year)

eriod (years)	River inflow (Qr)	Precipitation (P)	Evaporation (E)	Water withdrawal (Qa)	Balance (ΔV)
1980–1990	292	78	320	2,5	+47,5
1991–2000	280	75	335	3,2	+17
2001–2010	270	72	355	3,8	−16,8
2011–2020	260	70	362	4,1	−16,1
2021–2025	255	68	368	4,5	−49,5

The table demonstrates a transition to a negative water balance beginning in the early twenty-first century, indicating a persistent deficit in the Caspian Sea's water budget.

Impacts on Coastal Ecosystems. Analysis of satellite data and field observations revealed the following changes:

1. Reduction of wetland and salt-marsh ecosystems. The area of coastal wetlands in the Kurayty region decreased from 230 km² in 1990 to 90 km² in 2024.

2. Transformation of vegetation. The distribution areas of halophytic vegetation decreased by approximately 40%.

3. Impacts on fauna. Duck and wader populations declined by 30–35%, according to ornithological surveys conducted in 2023. The shallowing of spawning habitats has disrupted the spawning migrations of sturgeon and herring species.

4. Socio-economic consequences. These include the loss of commercial fishing grounds in the Fort-Shevchenko and Bautino areas, soil salinisation, pasture degradation, and a decline in the recreational attractiveness of coastal territories.

According to the estimates, every 10 cm decrease in sea level results in the degradation of approximately 250 km² of coastal ecosystems, including wetlands, salt marshes, and deltaic channels [8].

Spatial Modelling and Projections up to 2050. Modelling based on CMIP6 scenarios indicates a potential decline in the Caspian Sea level by 2050.

Table 2. Projected changes in the Caspian Sea level up to 2050

CMIP6 scenario	ΔTemperature (°C)	ΔPrecipitation (mm/year)	ΔEvaporation (mm/year)	Projected sea-level decline (m)
SSP1-2.6	+1.3	+2.5	+4.8	−1.2
SSP2-4.5	+2.1	+1.0	+8.5	−2.4
SSP5-8.5	+3.8	−3.0	+14.3	−3.2

Even under the moderate SSP2-4.5 scenario, a further decline in sea level is expected, potentially resulting in large-scale transformations of coastal landscapes.

Environmental and Management Recommendations. Based on the research findings, the following priority measures are proposed:

- Establishment of environmentally sustainable buffer zones in areas experiencing active shoreline retreat;
- Restoration and conservation of wetlands and salt marshes as natural filtration systems and regulators of the local microclimate;
- Implementation of a permanent environmental monitoring system for sea-level fluctuations and coastal ecosystem conditions, combining satellite observations with ground-based monitoring stations;
- Coordination of water resource management in the Volga and Ural river basins, including minimisation of anthropogenic water withdrawals and regulation of river flow with due consideration of the ecological requirements of delta ecosystems;
- Strengthening international cooperation among Caspian littoral states to develop coordinated adaptation strategies [4, 5].

Study Limitations and Future Research Directions

Study limitations. The main limitations include the heterogeneity of observation time series across different coastal sectors and uncertainties associated with climate scenario projections.

Future research directions. Further research should focus on refining assessments of climatic impacts using CMIP7 scenarios, developing improved models for water resource management at the basin scale, and conducting comprehensive geoecological surveys of coastal areas [6].

Conclusion. The analysis confirms that the decline in the Caspian Sea level during 1980–2025 has been driven by a combination of climatic and anthropogenic factors, primarily rising mean air temperatures, increased evaporation from the sea surface, and reduced river inflow.

The identified changes have resulted in the degradation of coastal wetland ecosystems, declining populations of waterbirds and commercially important fish species, soil salinisation, shoreline transformation, and the loss of valuable fishing grounds.

Mitigating these adverse impacts requires an integrated approach involving the restoration of degraded ecosystems, the development of long-term environmental monitoring systems, adaptation of economic activities, and coordinated water resource management among Caspian littoral states in the context of ongoing climate change.

Particular importance should be given to accounting for regional socio-economic risks and implementing scientifically based scenarios for the sustainable long-term development of the Caspian coastal territories.

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КАСПИЙ ТЕҢІЗІ ДЕҢГЕЙІНІҢ ДИНАМИКАСЫ ЖӘНЕ ЖАҒАЛАУ ЭКОЖҮЙЕЛЕРІНІҢ ЭКОЛОГИЯЛЫҚ ТҮРЛЕНУІ

Нағманов Д.Г., Бауыржанқызы М.
«Аль-Фараби Оперейтинг» ЖШС, Ақтау қ., Қазақстан
e-mail: diasnagmanov@mail.ru, e-mail: Madina.bauyrzhankyzy@gmail.com

Андатпа. Мақалада 1980–2025 жылдар аралығында Каспий теңізі деңгейінің өзгеруінің жағалаулық экожүйелердің жағдайына әсеріне кешенді талдау жасалған. Зерттеу көпжылдық гидрометеорологиялық бақылаулар деректерін, спутниктік зондтау материалдарын және өңірлік экологиялық зерттеулердің нәтижелерін жинақтауға негізделген. Теңіз деңгейінің ауытқуының тұрақты ұзақмерзімді үрдістері, гидрологиялық тепе-теңдіктің өзгеруі және биоалуантүрліліктің кеңістіктік динамикасы Қазақстан, Ресей және Түрікменстан жағалау секторларында анықталды. Каспий теңізі деңгейінің орташа төмендеу жылдамдығы шамамен жылына 6,4 см екені анықталып, бұл жағалаулық және батпақты экожүйелердің деградациясына, су құстарына тән популяциялардың қысқаруына, жағалау сызығының трансформациясына және балықтардың негізгі уылдырық шашу алаңдарының жойылуына әкелетіні көрсетілді. CMIP6 климаттық сценарийлерін пайдалана отырып, 2050 жылға дейін теңіз деңгейі мен экожүйелердегі ықтимал өзгерістерге болжам жасалды. Алынған нәтижелер негізінде бейімделу шараларының, экологиялық басқарудың және ұзақмерзімді мониторинг жүйесін қалыптастырудың басым бағыттары ұсынылды. Зерттеу нәтижелері өңірдегі климаттық өзгерістердің күшеюі жағдайында табиғатты қорғау мен табиғи ресурстарды ұтымды пайдалану бойынша аймақтық стратегияларды әзірлеуде қолданылуы мүмкін.

Түйін сөздер: Каспий теңізі, теңіз деңгейі, жағалаулық экожүйелер, гидрологиялық баланс, климаттың өзгеруі, ортаның деградациясы, биоалуантүрлілік, бейімделу.

ДИНАМИКА УРОВНЯ КАСПИЙСКОГО МОРЯ И ЭКОЛОГИЧЕСКАЯ ТРАНСФОРМАЦИЯ ПРИБРЕЖНЫХ ЭКОСИСТЕМ

Нагманов Д.Г., Бауыржанкызы М.
ТОО «Аль-Фараби Оперейтинг», Актау, Казахстан
e-mail: diasnagmanov@mail.ru, e-mail: Madina.bauyrzhankyzy@gmail.com

Аннотация. В статье представлен комплексный анализ влияния изменения уровня Каспийского моря на состояние прибрежных экосистем в период 1980–2025 гг. Исследование основано на обобщении данных многолетних гидрометеорологических наблюдений, материалов спутникового зондирования и результатов региональных экологических исследований. Выявлены устойчивые долговременные тренды колебаний уровня моря, изменения гидрологического баланса и пространственная динамика биоразнообразия в казахстанском, российском и туркменском секторах побережья. Установлено, что средняя скорость снижения уровня Каспийского моря составляет около 6,4 см в год, что приводит к деградации прибрежных и болотных экосистем, сокращению численности водоплавающих птиц, трансформации береговой линии и утрате ключевых нерестилищ промысловых видов рыб. Выполнено прогнозирование возможных изменений уровня моря и экосистем до 2050 года с использованием климатических сценариев CMIP6. На основе полученных результатов предложены приоритетные меры адаптации, экологического управления и формирования системы долгосрочного мониторинга. Результаты исследования могут быть использованы при разработке региональных стратегий охраны природы и рационального природопользования в условиях усиливающихся климатических изменений региона [1].

Ключевые слова: Каспийское море, уровень моря, прибрежные экосистемы, гидрологический баланс, климатические изменения, деградация среды, биоразнообразие, адаптация.