ГЕОІНФОРМАТИКА

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MULTI-TEMPORAL NDWI-BASED ASSESSMENT OF WATER RESOURCES AND COASTAL CHANGES IN THE ABSHERON PENINSULA, CASPIAN SEA

(Представлено членом редакційної колегії д-ром геол. наук, проф. Д. О. Ляшенком)

Background. *Global warming has also caused drought in coastal areas. This is especially a pressing issue for urban areas located on the coast. Our study area, the Absheron Peninsula, is located on the western coast of the Caspian Sea. Located in a semi-desert and dry-desert climate, this area is home to the country's most important economic, administrative and social center, Baku. This both causes and is affected by climate change.*

Methods. *During the study, we used satellite image analysis to analyze water resources in the area. For this, we processed satellite images from 2001, 2013 and 2023 using ArcGIS software. The 2001 satellite images were obtained from Landsat 5, the 2013 images from Landsat 8 and the 2023 images were obtained mainly from Landsat 9 satellites.*

Results. *As a result of the analysis, it was determined that the water level in the lakes located on the peninsula has decreased significantly. Even the water of the Caspian Sea has receded in coastal areas. This is one of the most important problems for the highest and most densely populated urban area.*

Conclusions. *The analysis of multi-temporal satellite imagery shows a clear and continuous decline in water resources across the Absheron Peninsula over the past two decades. Both inland lakes and the Caspian Sea coastline have experienced significant water loss, reflecting the intensifying impacts of climate change in this semi-desert region. These changes pose serious environmental and socio-economic risks for Baku, highlighting the urgent need for sustainable water management and climate-resilient urban planning.*

Keywords: *climate change, Remote Sensing, Caspian Sea, Absheron peninsula, climate action.*

Background

The most important factors determining the climate of the world's largest water basin by area are its geographical location (Berdimbetov et al., 2020), water exchanges between different parts of the sea (Berdimbetov et al., 2024), the influence of the surrounding land areas on it, as well as the different nature of atmospheric circulations (Dahal et al., 2025). In particular, the most important characteristic of the sea climate is the predominance of anticyclonic weather conditions here (Ciampittiello, Marchetto, & Boggero, 2024), along with the sharp change in temperature throughout the year, the windy and cold winter in the north, the warm winter in the south of the sea, and the calm, dry and warm weather over the Caspian in the summer.

The main factors that create currents in our study area are water currents (Al-Halbouni et al., 2022), the shape of the coasts, underwater relief, sea depth, water density variability, wind, and others. The most important of these factors is wind. In general, we can describe the current system in this way. These northerly winds, which prevail over the Caspian Sea throughout the year, create drift currents from north to south, mainly along its western shores, as a result of which these water flows are continuously directed to the Absheron Peninsula and are divided into 2 branches.

In the south of the Caspian Sea, more precisely, between the mouth of the Kura River and the Absheron Peninsula, there are local anticyclonic, i.e. clockwise, currents. In the Middle Caspian, there are flows that are southeasterly in the direction of the western shores. Starting from the Absheron Peninsula and moving northward, the speed of the currents in weak winds is 10–20 cm/s, while

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this indicator is observed in moderate winds at 30–40 cm/s, but in strong winds the speed of movement is 60–100 cm/s.

In the southern Caspian, in the Baku Archipelago region, we can say that the southern currents, which are observed at a speed of 10 cm/s, have a particular advantage. It should also be noted that in this area, the maximum flow speed of 40–50 cm/s was observed during the period of strong north-westerly winds observed here. In the South Caspian, southerly flows are observed along the eastern coast of the area during the April-September period throughout the year. The average speed of these flows varies, being especially high in strong winds and 50–60 cm/s, and less in moderate winds, i.e. 15–30 cm/s (Amanova, Hajiyeva, & Jafarova, 2024).

To ensure the methodological framework is firmly rooted in the regional context of the South Caspian, we have updated the literature review to prioritize local studies concerning the specific lithological, hydrological, and geomorphological characteristics of the Absheron Peninsula. This approach replaces previous references to disparate endorheic basins, allowing for a more accurate interpretation of coastal erosion and accretion processes that are unique to the local tectonic and climatic environment of Azerbaijan.

Although existing studies are mainly focused on the study of individual hydrometeorological indicators or local water bodies, a complex assessment of the combined impact of climatic and geological factors in multi-temporal and spatial terms has not been sufficiently carried out. In this regard, long-term analysis of the dynamics of water resources on the Absheron Peninsula using the capabilities of remote sensing and geographic information systems is relevant both for filling the scientific gap and for practical decision-making processes.

The dynamics of the Caspian Sea level are expressed here as the cumulative decline relative to the -27.0 m (BS) baseline. Historical moitoring data indicates a progressive lowering of the sea level: a recorded drop of 0.6 m in 2007, which deepened to 0.9 m in 2020, and reached 1.1 m by 2023. These values represent the vertical recession of water surface, which, given the shallow bathymetry of Absheron coastal zone, translates into a significant horizontal of shoreline.

The hydro-dynamics of the Absheron Peninsual are strongly influenced by the interplay between large-scale Caspian anticycllonic circulation and regional arid climate patterns. The dominant northerly winds drive coastal currents toward the Absheron Peninsula, which physically define the sediment transport and shorline stability of the Baku Archipelago. However, the connectivity between these macro-scale marine processes deficits and regional groundwater recharge mechanisms. Persistent anticyclonic weather conditions, characterized by high evaportranspiration rates and limited precipitation, exacerbate the water deficit in these isolated inland basins, while the retreating Caspian Sea level reduces the potential for sea-to-lake groundwater exchange, further accelerating the desiccation process observed in the inland water bodies.

The main objective of this study is to assess the spatiotemporal dynamics of water resources on the Absheron Peninsula using NDWI-based remote sensing analysis for 2001, 2013, and 2023. The specific tasks include: (1) mapping water bodies and their changes over time, (2) regionalizing the study area according to the intensity of water resource changes, (3) analyzing anthropogenic impacts along the AB profile, and (4) monitoring shoreline and island area variations using historical satellite imagery from 1984–2025. These tasks ensure a comprehensive understanding of both natural and human-induced factors affecting water resources in one of Azerbaijan's most densely populated and economically active regions.

Our findings demonstrate a significant decline in inland water bodies and a retreat of the Caspian Sea shoreline, consistent with previous studies on regional water scarcity. However, unlike broader basin-scale analyses, this study provides detailed local-scale mapping of NDWI dynamics, the first systematic AB profile assessment for the Absheron Peninsula, and quantification of island area expansion (Chilov, Pirallahi, Shahdili) over four decades. This comparative approach highlights both the consistency with prior research and the novel contribution of fine-scale, multi-temporal remote sensing analysis for local water resource management and planning.

Methods

During the study, we used the NDW index to study water resources and water basins.

Description of values: Water bodies have values greater than 0.5 (Salehie et al, 2022). Vegetation has smaller values, which makes vegetation easier to distinguish from water bodies (Stakhiv et al., 2025). Built-in features have positive values between zero and 0.2 (Deroin, 2025).

$$NDWI = (Green - NIR) / (Green + NIR).$$

NDWI values can range from –1 to 1 (Dube, Shekede, & Massari, 2023).

Index values between –1 and 0 indicate surfaces without vegetation or water; values closer to 0 indicate areas with low vegetation cover or high water stress; values between 0 and 1 indicate deeper water bodies (Titolo, 2021).

To minimize the spectral confusion between water bodies and built-up areas, we applied an additional masking technique. Pixels identified as built-up with positive NDWI values were cross-referenced with high resolution Google Earth imagery and corrected through manual classification, ensuring that the final NDWI results accurately represent actual water surface areas rather than urban infrastructure interference.

Results

We have compiled and analyzed maps of our study area reflecting the NDW (Normalized difference water index) index in 2001, 2013 and 2023 (Fig. 1). In this case, we used data from Landsat 5 and 8 satellites.

As a result of the analysis, 5 classifications were distinguished in the study area based on the index indicators. According to these classifications, areas with an index of less than –0.2 in 2001 accounted for 81.9 % of the study area, 4.2 % in 2013, and 5.6 % in 2023, while areas with an index of –0.02–0 accounted for 13 % of the study area in 2001, 91.6 % in 2013, and 91.8 % in 2023. Areas with this index of 0–0.1 covered 0.4 % of the study area in 2001, 0.9 % in 2013, and 1.4 % in 2023; areas with an index of 0.1–0.2 covered 0.4 % of the study area in 2001, 2.1 % in 2013, and 1.1 % in 2023; areas with an index of more than 0.2 covered 4.3 % of the study area in 2001, and 1.2 % in 2013.

If we look at the results of the index comparison, the most dramatic change in 2001–2013 was observed in areas where the index was less than –0.2 and more than 0.2, with a sharp decrease in area, and an increase in areas where the index was –0.2–0.2. In 2013–2023, the area where the index was higher than 0.1 decreased sharply (Tab. 1).

Using the capabilities of ArcGIS software, the dynamics of the NDW index in 2001–2013 and 2013–2023 were analyzed and mapped according to 4 classifications based on a comparison of different years (Fig. 2).

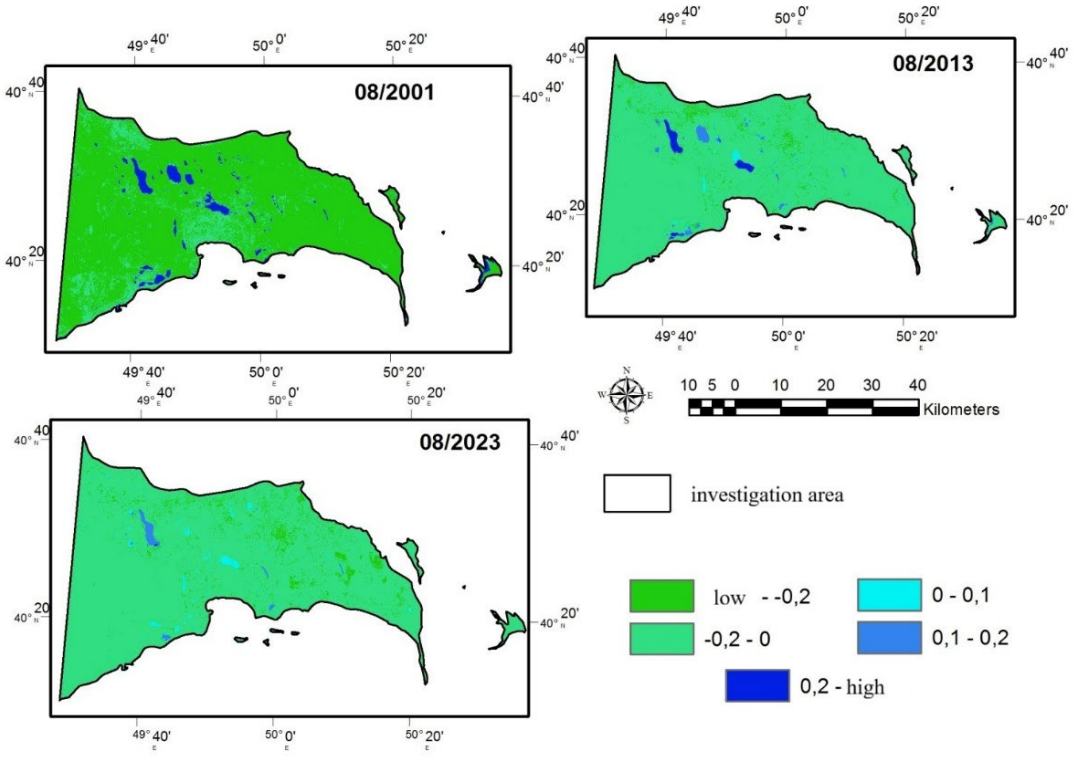


Fig. 1. NDW index and its dynamics
Source: The map was generated by the authors based on Landsat 5, 8, and 9 satellite data.

Table 1

Statistical indicators of the dynamics of the NDV index

№	NDW index		Area 2001		Area 2013		Area 2023		Dynamics in 2002–2013		Dynamics in 2013–2014	
			Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
1	low	–0.2	1648.9	81.9	85.5	4.2	112.4	5.6	–1563.4	–94.8	26.9	31.4
2	–0.2	0	262.7	13	1842.2	91.6	1847.7	91.8	1579.5	601	5.5	0.3
3	0	0.1	7.4	0.4	18.9	0.9	28.5	1.4	11.5	157	9.6	50.8
4	0.1	0.2	7.1	0.4	41.2	2.1	22.8	1.1	34.1	483	–18.4	–44.8
5	0.2	high	86.5	4.3	24.7	1.2	1.2	0.1	–61.8	–71	–23.5	–95.1
6	total		2012.5	100	2012.5	100	2012.5	100				

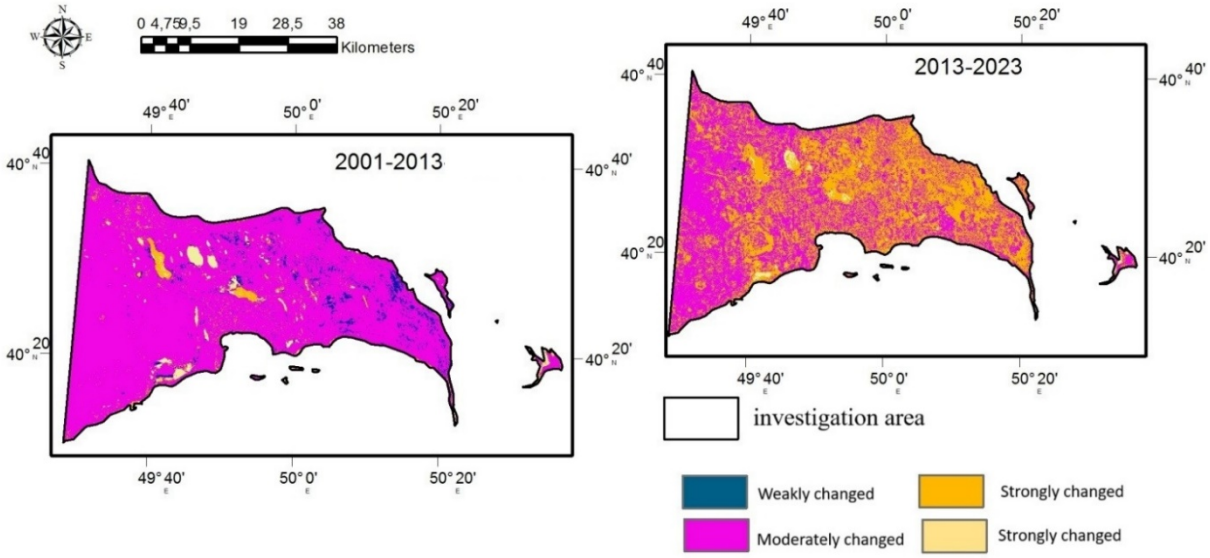


Fig. 2. Regionalization of the study area based on the dynamics of the NDW index in 2001–2013 and 2013–2023
Source: The map was generated by the authors based on Landsat 5, 8, and 9 satellite data.

It was determined that weakly changed areas accounted for 2.8 %, moderately changed areas for 3.8, strongly changed areas for 89.5 %, and intensely changed areas for 3.8 % during the 1st period. However, during the 2nd period, weakly changed areas accounted for 1.4 %, moderately changed areas for 47.2 %, strongly changed areas for 51.2 %, and intensely changed areas for 0.1 % (Tab. 2).

Table 2

Statistical indicators of the regionalization of the study area based on the dynamics of the NDW index in 2001–2013 and 2013–2023

№	NDW index	Area in 2002–2013		Area in 2013–2014	
		Km^2	%	Km^2	%
1	Weakly changed	57	2.8	28.3	1.4
2	Moderately changed	76.8	3.8	950.9	47.2
3	Strongly changed	1801.5	89.5	1030.8	51.2
4	Intensively changed	77.2	3.8	2.5	0.1
6	Total	2012.5	100	2012.5	100

During the study, in order to conduct more accurate analyses, we constructed an AB profile in the study area. This profile extends from west to east for a distance of 65 km. The change in the index along the profile and its comparison in different years more accurately characterizes the anthropogenic changes occurring in the landscapes (Fig. 3).

In 2001, the NDW index indicator on the AB profile takes the highest value at a distance of 42 km from point A in the west, and the lowest at a distance of 35 and 50 km (Fig. 4).

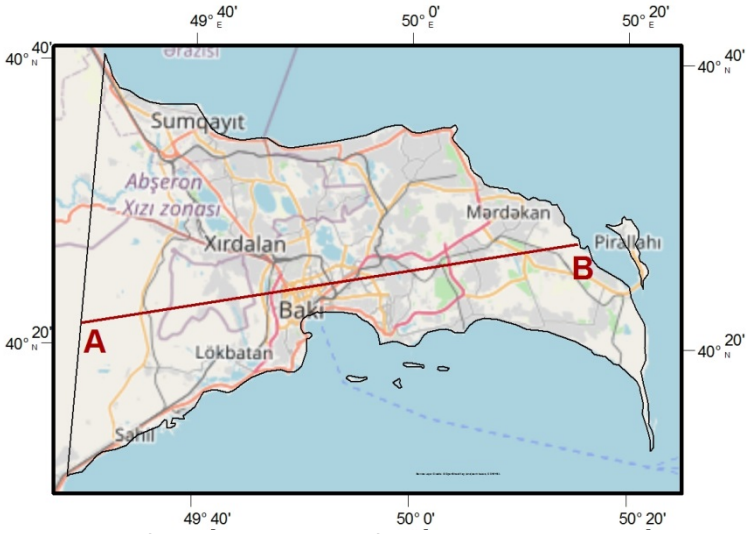


Fig. 3. AB profile line at a distance of 65 km on the Absheron Peninsula

Source: The map was generated by the authors based on Google Earth imagery.

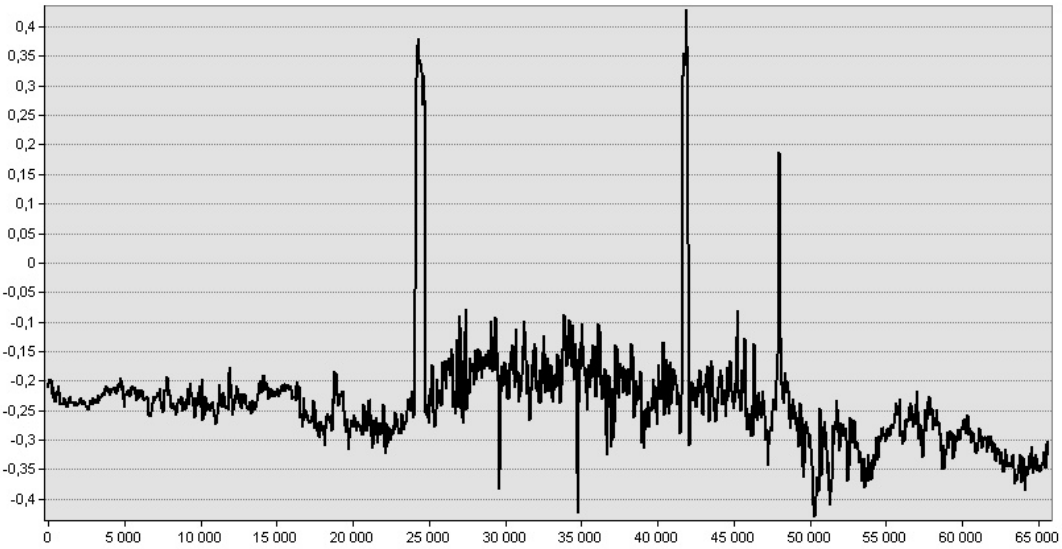


Fig. 4. Change in NDW index along the AB profile line in 2001

The largest value of the NDW index along the AB profile in 2013 was observed at a distance of approximately 42 km from the starting point of the profile, and the smallest value was observed at a distance of 58 km (Fig. 5).

The largest value of the NDW index along the AB profile for 2023 was observed at a distance of approximately 42 km from the starting point of the profile, and the smallest value was observed at a distance of 37 km (Fig. 6).

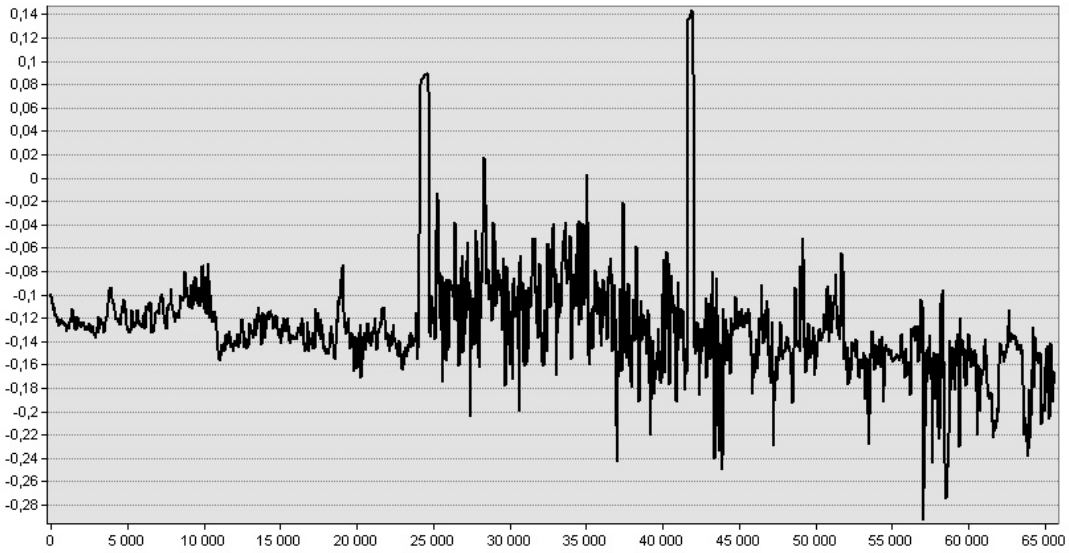


Fig. 5. Change in NDW index along the AB profile line in 2013

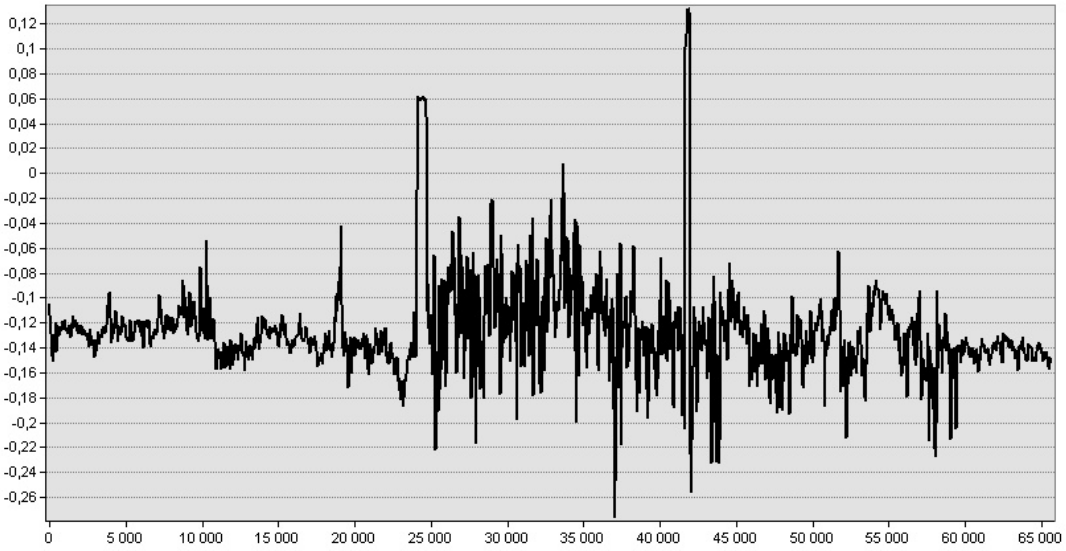


Fig. 6. Change in NDW index in 2023 along the AB profile line

We also used Google Earth and Google Earth Pro programs in our study area. For more accurate analysis, we conducted a study on the Absheron Peninsula based on satellite images from January 1984, 2006 and 2025. At this time, we selected study points near Jeyranbatan, Novkhani, Boyukshor, Zygh, Badamdar and Lokbatan. As a result of the analysis, we observed that water bodies in these areas were shrinking and were eventually replaced by residential facilities (Fig. 7 a, b, c).

Also, to monitor the dynamics of the water level in the sea, we vectorized the land border in the form of a satellite image of December 1990 in the area of Pirallahi, Chilov Islands and Shahdili. Then we compared it with January 2025 (Fig. 8, 9). As can be seen, the water level has decreased significantly and the land area has increased.

As a result of the level fluctuations of the Caspian Sea in 1990–2024, it was determined that the area of Chilov Island increased from 1200 ha to 2100 ha, the area of Pirallahi Island from 1300 ha to 2400 ha, and the area of Shahdili from 368 ha to 1300 ha. In particular, a large water area in the western direction of Chilov Island has turned into land, which, according to our calculations, covers an area with a width of 1462 m (Fig. 10 a, b, c).

The study is one of the first to use multi-temporal (2001–2013–2023) satellite data and the NDWI index to assess the dynamics of water resources on the Absheron Peninsula. Within the scope of the study:

- the changes in the coastline and inland lake areas were accurately depicted on the map;
- the impact of anthropogenic and climatic factors was determined through regionalization and AB profile analysis;
- the area changes of Chilov, Pirallahi and Shahdili islands were numerically calculated.

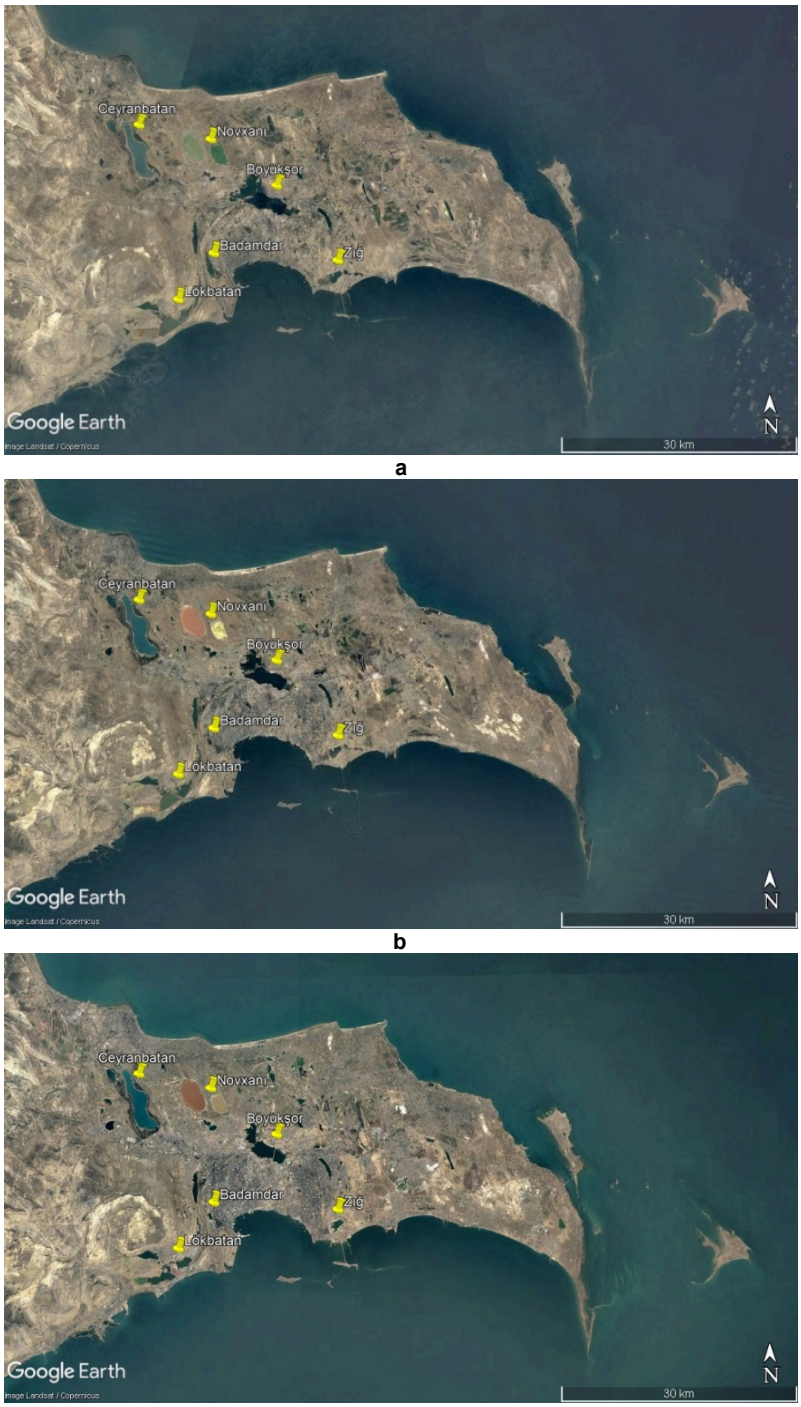


Fig. 7. Absheron Peninsula: a – 1984; b – 2006; c – January 2025
Source: The map was generated by the authors based on Google Earth imagery.

These results contribute to both cartographic theory and water resources management and spatial planning practices, and create an important database for the sustainable development of the region.

Practical recomemendations. Based on the observed water resource depletion and coastal retreat, we propose the following actions for sustainable urban management:

1. Buffer zones. Establish protected zones around inland lakes to prevent residental encroachment and preserve groundwater recharge capacity.

2. Urban planning. Integrate our multi-temporal NDWI mapping into Baku's master plan to identify high-risk zones for coastal erosion.

3. Monitoring network. Implement a systematic monitoring system for local aquifers to mitigate salinization risks linked to sea-level fluctuations.

4. Infrastructure resilience. Future coastal projects must incorporate the identified shoreline dynamics to avoid long-term environmental hazards.



Fig. 8. Pirallahi, Chilov Islands and Shahdili area (December 1990)
Source: The map was generated by the authors based on Google Earth imagery.



Fig. 9. Pirallahi, Chilov Islands and Shahdili Territory (January 2025)
Source: The map was generated by the authors based on Google Earth imagery.

Discussion and conclusions

The conducted remote sensing analysis clearly demonstrates that the Absheron Peninsula and the adjacent Caspian coastal zone have undergone significant hydrological transformations over the past decades. NDWI-based assessments for 2001, 2013, and 2023 reveal a continuous reduction in water bodies, a shift in index classes toward drier conditions, and widespread landscape modification. The regionalization results indicate that strongly and moderately changed areas dominate both study periods, reflecting the cumulative influence of climate change, sea-level fluctuations, and anthropogenic pressure.

The analysis reveals significant hydrological decline on the Absheron Peninsula. NDWI assessments for 2001–2023 shows a continuous reduction in water bodies and shoreline retreat. The AB profile confirms a sharp decline in water indices at the 42 km mark due to anthropogenic pressure. Numerical data validates coastal recession: Chilov island expanded from 1200 to 2100 ha, Pirallahi from 1300 to 2400 ha, and Shahdili from 368 ha to 1300 ha. These findings underscore the urgency of integrating multi-temporal remote sensing data into urban planning to mitigate climate-induced ecological risks.

Comparative analyses of multi-year satellite imagery (1984–2025) further confirm the shrinkage of inland lakes and the retreat of the Caspian Sea shoreline. The substantial expansion of Chilov, Pirallahi, and Shahdili islands provides physical evidence of declining sea levels and altered coastal geomorphology. These observations emphasize that water scarcity and environmental degradation are intensifying in one of the most densely populated and economically active regions of Azerbaijan.

Overall, the findings highlight the importance of continuous monitoring using remote sensing tools and the need for effective water resource management strategies to mitigate future ecological risks in the coastal Caspian environment.

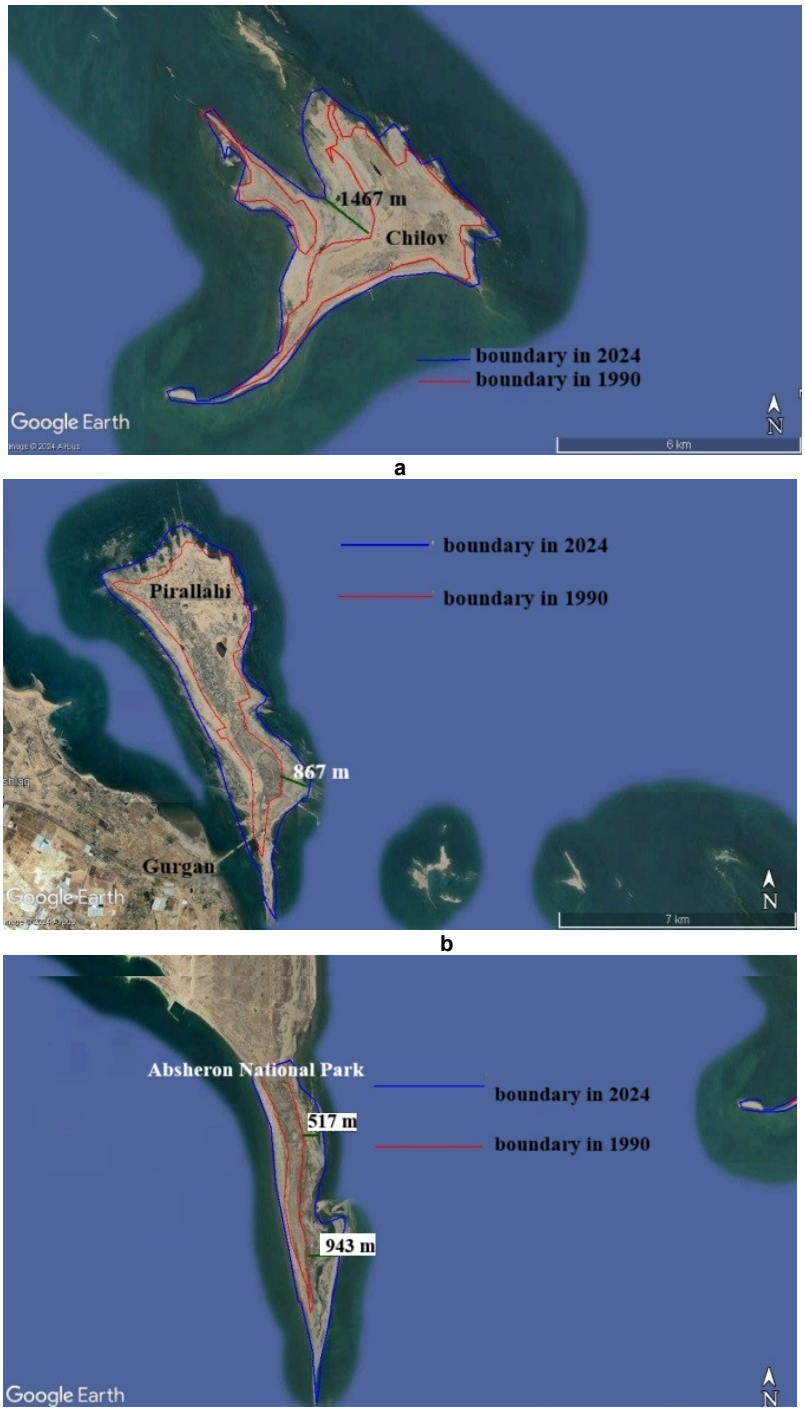


Fig. 10. Dynamics of the border of: a – Chilov Island; b – Pirallahi Island; c – Shahdili territory in 1990–2024
Source: The map was generated by the authors based on Google Earth imagery.

Authors' contribution: Shahnaz Amanova – writing, investigation, methodology, formal analysis, conceptualization, data curation, mapping, supervision; Mariam Tsitsiagi – formal analysis, supervision; Firuza Jafarova – data curation, supervision; Afag Hajiyeva – investigation, writing, supervision; Leyla Ibrahimova – visualization, supervision.

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БАГАТОЧАСОВА ОЦІНКА ВОДНИХ РЕСУРСІВ І ЗМІН БЕРЕГОВОЇ ЛІНІЇ АПШЕРОНСЬКОГО ПІВОСТРОВА КАСПІЙСЬКОГО МОРЯ НА ОСНОВІ ІНДЕКСУ NDWI

Вступ. ***Глобальне потепління спричинило засуху, зокрема й у прибережних районах. Це питання є особливо гострим для міських територій, розміщених на узбережжі. Район нашого дослідження – Апшеронський півострів – розташований на західному узбережжі Каспійського моря. Перебуваючи в умовах напівпустельного та сухого пустельного клімату, ця територія є осередком найважливішого економічного, адміністративного та соціального центру країни – Баку. До того ж фіксується зміна клімату.***

Методи. ***У ході дослідження водних ресурсів регіону ми застосували метод аналізу для вивчення супутникових знімків. Для цього за допомогою програмного забезпечення ArcGIS було опрацьовано супутникові знімки за 2001, 2013 та 2023 рр. Супутникові знімки за 2001 р. було отримано з космічного апарата Landsat 5, за 2013 – з Landsat 8, а за 2023 – переважно зі супутників Landsat 9.***

Результати. ***Унаслідок аналізу було встановлено, що рівень води в озерах, розташованих на півострові, істотно знизився. Навіть у прибережних районах відбувається відступ вод Каспійського моря. Це є однією з найважливіших проблем для території з найвищим рівнем урбанізації та найбільшою щільністю населення.***

Висновки. ***Аналіз різночасових супутникових знімків демонструє чітке та безперервне скорочення водних ресурсів на всьому Апшеронському півострові впродовж останніх двох десятиліть. Як внутрішні озера, так і берегова лінія Каспійського моря зазнали значних втрат води, що відображає посилення впливу зміни клімату в цьому напівпустельному регіоні. Ці зміни зумовлюють серйозні екологічні та соціально-економічні ризики для Баку, підкреслюючи нагальну потребу в сталому управлінні водними ресурсами й адаптованому до кліматичних змін міському плануванні.***

Ключові слова: ***зміна клімату, дистанційне зондування, Каспійське море, Апшеронський півострів, боротьба зі зміною клімату.***

Декларація про генеративний штучний інтелект та технології, що використовують штучний інтелект. Під час підготовки цієї статті автори не використовували інструменти штучного інтелекту.

Declaration of Generative AI and AI-Assisted Technologies. During the preparation of this work, the authors did not use artificial intelligence tools.

Етична декларація. Дослідження є теоретичним аналізом відкритих джерел і не передбачає безпосередньої взаємодії з людьми чи тваринами. Відповідно, отримання спеціального етичного висновку для такого типу дослідження не потрібно.

Ethical Statement. This study is a theoretical analysis of public sources and does not involve direct interaction with humans or animals. Accordingly, formal ethical approval was not required for this type of research.

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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