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Satellite-Based Assessment of Water Level Variability And Economic Exposure In Azerbaijan's Caspian Sea and Strategic Inland Water Systems

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ABSTRACT

This study evaluates the water-level changes and economic vulnerability of the Caspian Sea coast and the strategic inland water systems in Azerbaijan using satellite altimetry, official statistics and a geographic information system analysis. Long-term water-level data from Caspian Sea were used in conjunction with data obtained from satellites for Mingachevir and Shamkir reservoirs, and for river systems of Kura and Araz. Socioeconomic indicators for the regions for 2024 were used to represent current economic exposure and water dependency for agricultural production, including population, population density, industrial output, capital investment, agricultural production, water abstraction, water consumption, water lost, and irrigation use. To add some context on water efficiency and water stress, national indicators concerning SDG 6.4.1, SDG 6.4.2, and agricultural freshwater withdrawals were added. Each variable was normalised and combined in an author developed Integrated Water Risk and Economic Exposure Index, aided by spatial classification and mapping using QGIS. The results show that there exists a high spatial variability of water related exposures, and the highest exposures occur in areas where high population density, industrial concentration, agricultural dependence and strategic water infrastructure coincide. The exposure was the highest in Baku, and several districts in the central part of agriculture, such as Agjabadi, Sabirabad, Shamkir, and Saatli, also had higher values. The results highlight the need to consider long-term hydrological change in conjunction with current socioeconomic vulnerability, rather than as a stand-alone environmental phenomenon. The study suggests a framework for an open and reproducible water-risk assessment and gives evidence for climate adaptation, coastal planning, irrigation management, investment in infrastructure, and regional development policy in Azerbaijan.

INTRODUCTION

Water security has emerged as a major environmental and economic challenge with climate change now impacting precipitation, evaporation, runoff, water availability, and the reliability of water-dependent ecosystems. These changes impact hydrological systems, as well as agriculture, food security, infrastructure, industry, public services and regional development. According to the Intergovernmental Panel on Climate Change, the water cycle is already being impacted at global scale, with an increasing risk for humans and nature that necessitates the need for improved monitoring and adaptation measures (IPCC, 2022, 2023).

The Caspian Sea plays a special role in this regard as the world's largest enclosed inland water body, which is highly responsive to change in river inflow, precipitation, air temperature and evaporation. Its level is primarily regulated by the regional water balance and is very sensitive to the climatic and hydrologic variability unlike the open ocean. Since the mid-1990s, satellite data compiled in National Aeronautics and Space Administration's (NASA) Global Water Monitor show a general decline in the level of the Caspian Sea, and recent studies suggest that this trend could be accelerated if atmospheric warming and increased evaporation continue (NASA, 2026; Chen *et al.,* 2017, 2023).

Variations in the Caspian Sea level are not a purely environmental issue for Azerbaijan. The national coastline is host to dense concentrations of settlements, industrial infrastructure, transport and logistics infrastructure, areas of significant tourism value, wetlands, agriculture and other economically important systems. A long-term decrease could change the capability of shoreline access, impact port and coastal infrastructure, reveal new areas of submergence, change wetland habitat, and increase planning and maintenance expenses. At the same time, short-term fluctuations and long-term decline may have varying impacts at different places; therefore, the physical change in water-levels should be considered in conjunction with the spatial distribution of population, investment, industry, agriculture and infrastructure.

Inland water systems are also important for the water security of Azerbaijan. The Kura and Araz rivers and large reservoirs (Mingachevir, Shamkir) are essential for irrigation, electricity generation, water supply for municipal and industrial needs, as well as ecosystem. One of the most significant of these man-made water bodies is the Mingachevir Reservoir, which is important for water storage and regional development (NASA Earth Observatory, 2010). This fluctuation in these rivers and reservoirs may thus have direct impacts on the productivity of agriculture, energy generation, water

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supply and the economic viability of dependent districts. Traditional monitoring on the ground is still critical, although restricted by partial spatial coverage, variations in observation frequency, inaccessibility, and lack of consistency between monitoring systems. An alternative method is to use satellite altimetry to make repeat, comparable measurements of water surface elevation over extended time periods. The Global Water Measurements platform is available for access to NASA-satellite-derived water-height products over the Caspian Sea and archives as well as near-real-time satellite-derived water-height products for the Caspian Sea (NASA, 2026). A Database for Hydrological Time Series of Inland Waters combines multi-mission satellite altimetry data to create water-level time series for lakes, reservoirs, rivers and wetlands for inland waters (Schwatke *et al.,* 2015).

But hydrological observations only form part of socio-economic risk. Risk is also influenced by the exposure of populations and productive sectors, and the concentration of exposed populations and water-dependent activities. Hence, a drop in the water level in a wilderness is not of the same economic importance as a drop in the water level in the vicinity of a large urban, industrial, agricultural or transport centre. The current research thus distinguishes between the physical water-level trend and modern socio-economic exposure. The hydrological context is identified based on long-term satellite observations, while the statistics for the reference year 2024, provided by the official entities, offer a snapshot of the current situation in terms of population size, industrial activity, investments, agriculture production, water abstraction, water use, irrigation and water losses.

It is methodologically significant that the same socioeconomic year of reference has been used. It ensures that you can compare variables over time, and prevent regional indicators from different years being mixed. Hence, no attempt is made in this study to estimate changes of economic exposure over the whole period of satellite observation. Rather, it considers the existing spatial distribution of exposure to the long-term water-level trend observed. The study has a methodological dimension, with the socioeconomic exposure assessment being a static one within a long-term trend analysis of the hydrological situation.

Sustainable Development Goal 6 is used to refer to the overall water-governance landscape. Indicator 6.4.1 evaluates the change in water-use efficiency, measured as the ratio of economic value added (EVA) to water withdrawn, and Indicator 6.4.2 evaluates the ratio of freshwater withdrawn (RWFWR) to available renewable freshwater resources, taking into account environmental flows (UN-Water (n.d.-a, n.d.-b)). These indicators are relevant for Azerbaijan as water-related vulnerability is not only related to water availability, but also on the efficiency of water use and the extent of economic sectors' dependence on freshwater withdrawals.

Economic and institutional conditions are also crucial. The earlier studies conducted in Azerbaijan revealed the significance of public regulations, monetary policies, investments, and the ability to react to external shocks for the national development and resilience (Zeynalova, 2019; Guliyeva *et al.,* 2021). Guliyeva *et al.* applied normalized indicators and integrated assessment framework to analyze the fiscal risk-macroeconomic development nexus, which may serve as a methodological reference for composing a composite indicator in the Azerbaijani context. Zeynalova's work also highlights the importance of regulatory tools in the process of development of the state in globalised conditions. These perspectives are pertinent as adaptation to the water-related risks will not only involve monitoring but also coordinated investments, taxes, infrastructure planning, agricultural policies, and the development of regions.

Green finance and sustainable investment also can be used to promote the development of water infrastructure, monitoring networks, irrigation upgrades, water storage facilities, and regional development that is climate resilient and adaptation oriented. Recent studies on Azerbaijan have shown that the green transition in the country needs to be supported by public policies, private investments, international financial support and enabling infrastructure (Sadiqov *et al.,* 2026). While that research was on solar energy, the overarching finding in that research was that coordinated financial, institutional and infrastructure mechanisms are necessary for environmental transition and the same applies to water security and climate adaptation.

Although the Caspian Sea and Azerbaijan's inland water systems are significant, the studies that have been conducted tend to look at hydrological change, economic development, agricultural dependency or water stress in isolation. There are a few studies that incorporate long-term water-level data from satellites with district-level socioeconomic data within a repeatable GIS-based approach. In addition, there is no integrated national assessment of the exposure of Caspian coasts and dependency of agricultural and water-resources in the administrative units of Azerbaijan.

This study fills this gap by integrating satellite altimetry, official statistics, national SDGs indicators, international water use data and geospatial analysis. The empirical framework includes eight open-source research datasets on water-level variability in the Caspian Sea, selected inland water systems, point-based geospatial inventory, exposure of coastal economies, dependency of agriculture on water, water stress indicators, water-use efficiency, and an integrated risk index (Mammadov, 2026a–g; Mammadov & Bernardino, 2026). These datasets provide transparency, data traceability, and data reproducibility.

The study has a four fold objective:

1. To determine long-term changes in water level for the Caspian Sea and important inland water systems by Satellite altimetry;
2. To assess the current economic vulnerability and water dependence of agriculture with the help of official regional statistics from 2024;

3. to develop an Integrated Water Risk and Economic Exposure Index incorporating water-level context, economic exposure, agricultural dependency and national water stress;

4. To represent risk and exposure in a spatial context using maps, comparative tables, figures and diagrams in QGIS.

This study is unique in developing a simple, open data framework that connects physical hydrological change to current economic exposure. The outcomes are designed to feed into the coastal planning, irrigation management, water-security policy, investments in infrastructure, climate adaptation, and regional development in Azerbaijan.

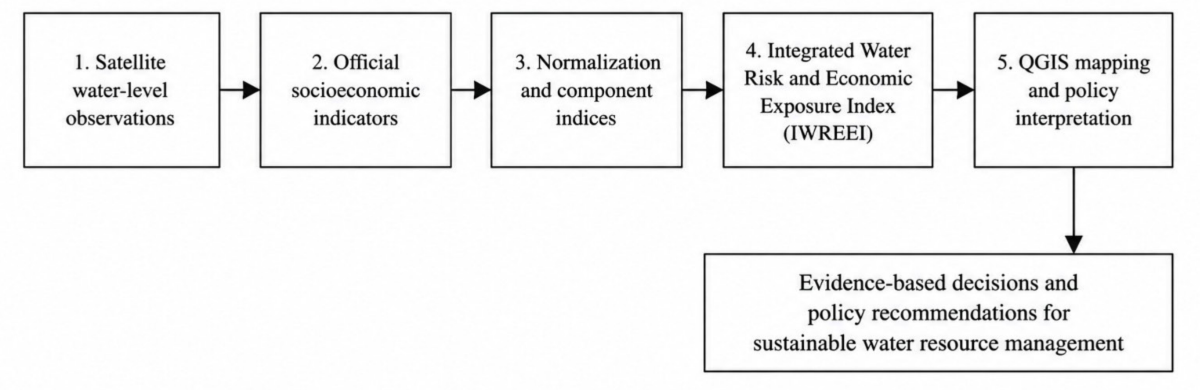

Figure 1: Conceptual framework of the study

LITERATURE REVIEW

Global scientific interest in the Caspian Sea has been growing over the years as the water level is directly related to the regional water balance, which is influenced by the regional climatic parameters, such as river discharge, precipitation, evaporation, temperature, and anthropogenic water consumption. It is an enclosed inland water body and has a fundamental difference from the global ocean, as its level does not respond first to global eustatic sea-level change. Rather, relatively small changes in climatic and hydrological inputs can have significant changes in its surface elevation and shoreline position.

Research based on satellite data has since brought to light solid evidence of a long-term drop in the level of the Caspian Sea since the mid-1990s. Integrating satellite radar altimetry and gravity observations, Chen *et al.* (2017 revealed that enhanced evaporation over the sea was the main driver to turn around the former positive trend. Their findings showed that satellite data can detect long term water level changes and the seasonal water level variations, and also it can help to differentiate the drivers of climatic and hydrological ones (Chen *et al.,* 2017).

This decrease is expected to persist and increase in the future under climate change. Samant and Prange (2023) developed a twenty-first-century water-balance change assessment in the Caspian based on the climate-model projections from the Earth System Models (ESMs) of the Coupled Model Intercomparison Project Phase 6 (CMIP6). Their results show that under multiple climate scenarios, an increase in evaporation will likely outweigh any increase in precipitation or river inflow, lead to an increasingly negative water balance, and result in significant future decreases in water level (Samant & Prange, 2023).

The impacts of the falling Caspian water level are not limited to hydrology. Recent geospatial studies indicate that even modest losses can result in changes to coastal ecosystems, loss of access to existing coastal protection, impact on endemic species, and increasing separation of the coast from permanent infrastructure. Court *et al.* (2025) have shown that future loss of many metres may have a significant impact on seal habitats, on shallow coastal ecosystems, on protected areas and on human infrastructure. This indicates that the Caspian Sea decline should be considered as an environmental, spatial, and economic problem and not solely a change in the water level (Court *et al.,* 2025).

The effects of water-level drop vary geographically. Shallow coastal areas can see significantly larger shoreline recession than steep coastal areas. Thus, the exposure of ports, transport facilities, industrial areas, settlements, wetlands, tourism assets, and agriculture land could vary according to the water level changes despite similar overall water-level changes. The spatial variation also enhances the relevance of GIS, as it allows the spatial integration of hydrological change with the spatial location of populations, economic activities, environmental sensitive areas and infrastructure.

Satellite altimetry has also gained more importance for the monitoring of inland water bodies. Satellite altimeters were originally designed for use in ocean observations but have since been used extensively in lakes, reservoirs, rivers, and wetlands. The main benefits of their use is that they are able to make repeat and consistent observations over large or inaccessible areas, particularly in areas where conventional gauge networks are incomplete and/or spatially fragmented.

The Database for Hydrological Time Series of Inland Waters is an important methodological development in this field. To overcome these issues, Schwatke *et al.* (2015) proposed a multi-mission approach to harmonize the water-level time series derived from observations from multiple satellite altimetry missions using a specific waveform retracking and outlier detection method. This approach enhances temporal continuity and allows monitoring of lakes, reservoirs, rivers and wetlands over long time periods (Schwatke *et al.,* 2015).

Satellite monitoring of inland waters is particularly important for Azerbaijan, where the strategic rivers and reservoirs play various economic roles. The Kura and Araz rivers, as well as reservoirs like Mingachevir and Shamkir, are used for irrigation, hydropower production, water storage, supply for cities, industry and ecosystem services. Changes in their water levels can, therefore, impact agricultural productivity, energy security, water supply and economic resilience of the region. Much of the literature in the field of satellite altimetry, however, focuses on the generation and validation of water level records, and fewer studies integrate water level records with subnational socioeconomic indicators.

This distinction is crucial since hydrological change is not necessarily an economic risk. The greater the exposure of populations, productive assets, infrastructure or water-based activities to the observed physical process, the greater the risk. This change in water level could be of little economic significance in an area of low population density but may have much more far-reaching consequences in areas near to a major transport, industrial, agricultural or urban centre. For this reason, environmental-economic assessment needs to take into account both physical change and socioeconomic exposure.

The literature on water governance also illustrates that physical water availability needs to be reported in conjunction with water use and economic efficiency. SDG Indicator 6.4.1 provides an indicator of the economic value added per unit of water consumption, indicating that economic growth is no longer as dependent on water use. Indicator 6.4.2 reports freshwater withdrawals against the available renewable freshwater resources, in consideration of environmental flow requirements. These indicators offer additional views on water-use efficiency and water pressures on country water resources (UN-Water (n.d.-a, n.d.-b)).

Especially relevant in this regard is the sector of agriculture, which is very sensitive to the availability of water, irrigation systems, and water-distribution efficiency. Crop structure, irrigation requirements, water abstraction, water consumption and distribution losses are also important factors affecting regional agricultural exposure, in addition to agricultural production volumes. Thus the water dependence of agricultural sector should be considered as a separate risk of country's water resources, particularly in the districts dependent on the Kura-Araz river system and the main reservoirs.

The use of composite indicators offers a useful way to merge physical, economic, agricultural, and water use variables. Normalization and aggregation create comparable scores of indicators in different units and combine them in a multidimensional index. But the composite index outcome is highly sensitive to the choice of indicators, normalisation procedure, weighting scheme and aggregation technique. For this reason, transparency and reproducibility are very important in the development of an integrated environmental-economic index.

Normalized indicators and additive aggregation are methodological precedents relevant to Azerbaijan, as in Guliyeva *et al.* (2021). They show how different economic indicators can be standardized and integrated into a single index to facilitate comparative evaluation and policy interpretation. While they studied fiscal policies and economic shocks, their methodological logic can be used in building integrated water risk – economic exposure indicators.

There are also important institutional and regulatory conditions since water-related risks can't be solved by environmental monitoring. Zeynalova (2019) speaks about the importance of state regulation and economic instruments in the process of supporting national development in the conditions of changes in the global environment. This perspective has relevance for water governance as adaptation may involve public investments, taxation and incentive schemes, modernisation of infrastructure, efficient water allocation and coordination of environmental and economic institutions.

Likewise, earlier studies on the green finance in Azerbaijan reveal that environmental transition requires a coordinated public policy, investment mechanisms, infrastructure development and institutional support. Sustainable investment necessarily involves a mix of government measures, private capital, international financing, and enabling structures, sustained by a combination of these, as Sadiqov *et al.* (2026) show. Their work is about solar energy but the overall implications are also applicable to water security and climate adaptation especially when capital is needed for monitoring system development, irrigation modernization, water storage infrastructure and regional development with climate adaptability.

From the literature reviewed, there are identified gaps. Firstly, Caspian Sea studies are mostly dedicated to climate drivers, water balances, shoreline evolution, biodiversity or impact on infrastructure. Second, satellite-altimetry studies mainly concentrate on the technical estimation of water-level time series. Third, the economic and agricultural literature typically evaluates regional development or water use with no direct link to the hydrological variability that is observed. Hence, few studies combine long-term satellite-derived observations, inland water-level data, district-level exposure to economic losses, dependency of agriculture on water, national water-stress indicators, and spatially classifiable GIS-based data under one single framework.

This study aims to fill this gap by integrating long-term observations of water levels from satellite-derived quantitative remote sensing with a common socioeconomic year (2024). The long-term observations are the physical hydrological context and the statistics for 2024 are a contemporary snapshot of population, industry, investment, agricultural production, water abstracted, water used for irrigation, water consumed and water lost. The distinction is important methodologically: the study does not postulate changes in socioeconomic exposure over the entire satellite period, but rather the spatial distribution of socioeconomic exposure in the present day under an observed long-term hydrological trend.

The originality of the study is therefore that it combines satellite altimetry, official regional data, SDG water indicators, open research data and spatial analysis in QGIS to create an Integrated Water Risk and Economic Exposure Index for Azerbaijan. This framework can facilitate comparison at administrative level and serve as a reproducible framework for coastal planning, irrigation management, water-security policy, infrastructure investment and climate adaptation.

MATERIALS AND METHODS

Study Area

The study is based on Azerbaijan, where water security has become one of the most critical environmental and economic problems, owing to climate variability, hydrological conditions and constant reduction of the Caspian Sea level. The country has a variety of water resources, such as the coast of Caspian Sea, big transboundary rivers (Kura, Araz), big artificial reservoirs, and many lakes in the country, where agriculture, industry, urban water supply, hydropower production, fish farming, and ecosystem services are practiced (FAO, 2024; World Bank, 2024).

The assessment makes a comprehensive review of all administrative districts of Azerbaijan, focusing on the strategically important water formations, such as the Caspian Sea, Mingachevir Reservoir, Shamkir Reservoir, Takhtakorpu Reservoir, Jeyranbatan Reservoir, Sarsang Reservoir, Varvara Reservoir, Kura River and Araz River. The choice of these water bodies was based on the important role they play in providing water supply, irrigation structure, economic production, biodiversity conservation and regional development for the country.

Compared to research that only takes hydrological observations, the present study extends environmental and socioeconomic aspects in a single spatial assessment framework to allow for a comparison of regional vulnerability and economic exposure throughout the country.

Data Sources

Several open-access satellite, governmental and international data was compiled to create the Integrated Water Risk and Economic Exposure Index (IWREEI). Water-level measurements from satellites were accessed from the DAHITI Database, providing consistent long-term water-level measurements for inland waters and the Caspian Sea. Extra hydrological observations were used to compare with NASA Global Water Monitor products to provide consistency in long-term trends.

Data on socioeconomic indicators, including the characteristics of population distribution, industrial production, agriculture, and irrigation dependence in regions was obtained from the State Statistical Committee of the Republic of Azerbaijan (AzStat, 2024). Data on water stress indicators and variables on agricultural water-use efficiency were collected from the FAO AQUASTAT and SDG 6 monitoring databases, complemented by additional environmental data from the World Bank Open Data portal.

All processed datasets in this study were independently archived in Zenodo under permanent DOI (Mammadov, 2026a–g; Mammadov & Bernardino, 2026), to enhance the transparency and reproducibility.

Table 1: summarizes the principal datasets employed throughout the analysis.

Data source	Provider	Spatial coverage	Temporal coverage	Purpose in the study
Caspian Sea satellite water-level observations	DAHITI Satellite Altimetry Database	Caspian Sea	1992–2026	Assessment of long-term water-level variability
Strategic inland water bodies dataset	DAHITI Satellite Altimetry Database	Major reservoirs and rivers of Azerbaijan	1992–2026*	Evaluation of inland water systems
Administrative boundaries	Humanitarian Data Exchange (HDX)	Azerbaijan districts	2024	Spatial analysis and GIS mapping
Economic exposure indicators	State Statistical Committee of the Republic of Azerbaijan (AzStat)	District level	2024	Regional socioeconomic assessment
Agricultural water dependency indicators	FAO AQUASTAT	National and regional	Latest available	Agricultural water-use assessment

National water stress indicators	SDG 6 Global Database / FAO	National	Latest available	Water stress evaluation
Satellite-derived environmental observations	NASA Global Water Monitor	Caspian Sea	1992–2026	Verification of long-term hydrological trends
Spatial visualization	QGIS 3.40	Azerbaijan	2026	Production of thematic maps and spatial analysis

Integrated Water Risk and Economic Exposure Index (IWREEI)
The Integrated Water Risk and Economic Exposure Index (IWREEI) is a new method that integrates hydrological observations with socioeconomic indicators to estimate relative exposure of administrative regions in the Republic of Azerbaijan to water-related risks.
The following are the 4 main components integrated:
- Hydrological context score
- Economic exposure score
- Agricultural Water Dependency Score
- National water stress context score

To make different units of variables comparable, all indicators were min–max normalized in a 0–100 range.
The normalization procedure is expressed as
$X' = [(X - X_{min}) / (X_{max} - X_{min})] \times 100$
where X' denotes the normalized indicator value.
The final integrated index was computed as
$IWREEI = 0.25H + 0.25E + 0.25A + 0.25W$
where
- H = Hydrological context score
- E = Economic exposure score
- A = Agricultural dependency score
- W = National water stress score

and wi represent weighting coefficients assigned equally to each component during the baseline assessment.

Table 2: Components used in constructing the IWREEI.

Component	**Indicator**	**Normalization**	**Weight**
Hydrological context	Satellite-derived water-level variability	Min–Max	0.25
Economic exposure	Population, industry, investment	Min–Max	0.25
Agricultural dependency	Irrigation and agricultural water use	Min–Max	0.25
National water stress	SDG 6 & FAO indicators	Min–Max	0.25

Spatial Analysis and Mapping
Spatial processing and visualization was performed with QGIS 3.40. Administrative district polygons were sourced from Humanitarian Data Exchange (HDX) and strategic water systems were represented using manually verified geospatial point datasets created during this research.
Adminstrative identifiers were used to join district level indicators to polygon layers and thematic maps were created using rule-based symbology. Areas were grouped into four categories: No available data, low, moderate, and high integrated water risk and economic exposure.
Incorporation of cartographic elements such as legends, north arrow, scale bar and labelled strategic water bodies to enhance interpretability. The last map presents the national picture of spatial differences in the combined hydrological and socioeconomic vulnerabilities.

Statistical Analysis
To summarize long-term trends of water-level changes and distributions of regional indicators, descriptive statistics were used. Satellite data were used for the more than thirty years to assess temporal variability in the Caspian Sea and the selected reservoirs.
Standardised indicator comparison was used instead of predictive modelling to compare hydrological conditions and regional socio-economic characteristics. The goal was not to predict future water levels, but to provide spatial patterns of integrated exposure that are important for water-resource planning and sustainable regional development.

RESULTS AND DISCUSSION
Variability of water level in the Caspian Sea
The satellite altimetry data processing showed that the water level of the Caspian Sea had a significant long-term trend during the period of study. The harmonised data set, covering the period from October 1992 to July 2026, included over 30 years of continuous observations from various satellite missions and were compiled using NASA Global Water Monitor (Mammadov, 2026b; NASA, 2026). A long observation period allows long-term hydrological trends and short-term fluctuations under the varying climatic conditions to be examined.
The complete satellite-derived time series used in the present study is shown in figure 2. The observations show that water levels underwent seasonal fluctuations in the whole period but the overall trend shows a steady fall. This slump was especially obvious since the mid-2000s and several of these years saw even more rapid lowering of the water surface. Such behaviour agrees with previous satellite-based investigations that associated recent Caspian Sea decline with increasing evaporation, rising

regional temperatures, and changes in the hydrological balance of the basin (Chen *et al.,* 2017; Samant & Prange, 2023).

According to the long-term observations, the Caspian Sea does not show a linear decrease pattern, but rather a series of multiannual decreases followed by a period of relative stability over a shorter time scale. Such behavior is a result of climatic variability, river inflow, atmospheric circulation and evaporation processes. Due to the enclosed nature of the Caspian Sea, relatively small variations in these factors can significantly affect the water balance of the Sea. Thus, satellite observations are essential for obtaining continual data not readily available from coastal gages (Schwatke *et al.,* 2015; NASA, 2026).

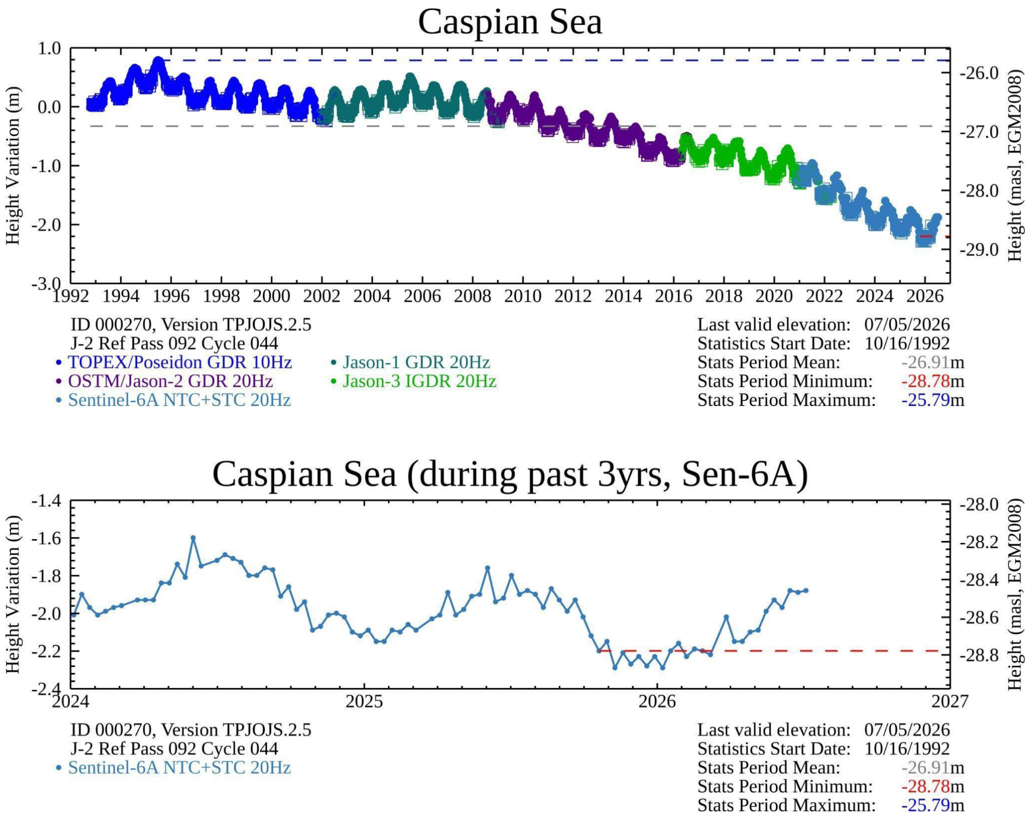

Figure 2: Long-term variability of the water level in Caspian Sea from satellite altimetry data (1992-2026).
Source: Mammadov (2026d), based on NASA Global Water Monitor (2026). Caspian Sea water levels (Target ID 000270). https://earth.gsfc.nasa.gov/gwm/lake/270

For easier interpretation of the long-term trend, the observations were also aggregated into a cleaned visualization of the general change direction on a graph while minimizing the number of individual measurements that led to the complexity of the graph, which was thousands of measurements. The strong downward trend observed throughout the data is clearly apparent in the processed version displayed in Figure 3.

A comparison of Figures 2 and 3 shows that periodic short-term variations are still discernible but do not change the long-term change direction. Rather, the

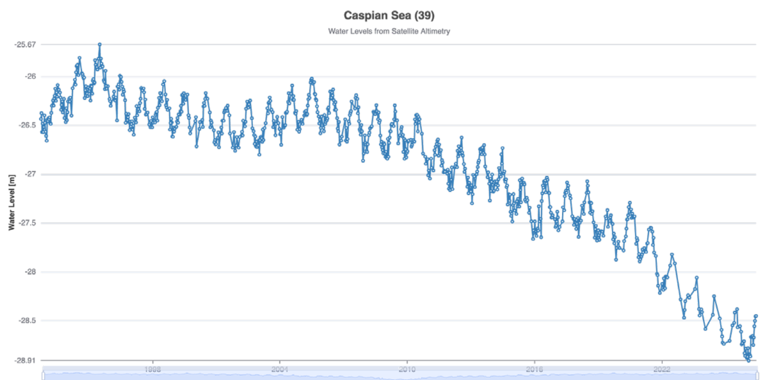

Figure 2: Processed satellite-derived Caspian Sea water-level trend used for analytical interpretation.
Source: Mammadov (2026d), based on DAHITI satellite altimetry observations.

processed visualization highlights the ongoing decline which is the underlying hydrological context of the current study. This distinction is important because the purpose of the study is not to forecast future water levels, but instead to assess economic vulnerability in the region as it exists in the context of an observed long-term hydrological trend.

The results obtained are in line with the recent international studies. Satellite gravity and radar-altimetry observations were used by Chen *et al.* (2017) to find that the evidence for changes in Caspian Sea water balance is robust, and that evaporation is one of the major processes contributing to the recent decreases. Similarly, Samant and Prange (2023) estimated that higher temperatures could lead to additional enhancement of evaporation in the twenty-first century, driven by various climate scenarios, contributing to ongoing water level declines. More recently, Court, *et al.,* (2025) showed that the ongoing decline of the Caspian Sea could significantly impact biodiversity, coastal wetlands, protected areas, transport infrastructure, and human settlements. This is corroborated by the results of the current study which has shown that the long-term decreasing trend is still present in the latest satellite-derived estimates up to 2026. But water level fall significance should not be viewed just from hydrological observation. Water-level reduction is only of economic significance if it impacts populated areas, industrial facilities, food production, transportation, or other socio-economic resources. Hence the trend shown here, based on satellite data, should be understood as the 'physical hazard' aspect of the overall assessment. This hydrological context is then considered alongside the regional vulnerability of Azerbaijan's economy, the water dependence of the country's agriculture, and the national water-stress indicators, to assess the spatial variability of integrated water-related risk in Azerbaijan.

Strategic Inland Water Systems

There was a significant variation between satellites in water-surface elevation ranges, periods of cover and uncertainty of the measurements for the selected inland water systems. The analysis accounted for the Mingachevir and Shamkir reservoirs, as well as the Kura and Araz rivers – the most important elements of Azerbaijan's water-management infrastructure, in terms of water storage, irrigation, hydropower and river regulation. Observations were from DAHITI, and the data was processed in the related open dataset created in this study (Mammadov & Bernardino, 2026; Schwatke *et al.,* 2015).

The results of the main description are given in Table 3. The four targets are quite different in terms of their elevation datum, basin morphology, observation period, and the geometry of the satellite track, so that the absolute value of water surface elevation should not be interpreted as water abundance relative to one another. Rather, ranges of minimum–maximum values, fluctuations over time and most recent observation are used to describe the behaviour of each individual water system.

Among four systems, the widest range of elevations observed was in the Mingachevir Reservoir, with a difference of 11.291 m between the lowest and highest elevations. It had a mean water-surface elevation of 73.042 m with the latest reading at 78.007 m. This relatively large distribution is a result of the regulated nature of the reservoir and the effects of seasonal inflow, water releases, irrigation demands, hydropower generation and storage management. The most recent data was at the high end of the range of data but not necessarily indicative of long-term security since the data also shows significant historical drawdown.

Table 3: Summary statistics of selected strategic inland water systems based on DAHITI satellite altimetry

Water system	Observation period	Number of observations	Minimum WSE, m	Maximum WSE, m	Mean WSE, m	Latest WSE, m	Latest observation
Mingachevir Reservoir	5 June 2016–9 March 2026	84	67.216	78.507	73.042	78.007	9 March 2026
Shamkir Reservoir	20 December 2018–12 May 2026	90	139.136	150.733	143.594	147.293	12 May 2026
Kura River	29 May 2016–25 April 2026	112	82.820	86.128	84.157	84.161	25 April 2026
Araz River	12 January 2019–4 June 2026	94	796.605	799.263	797.574	798.826	4 June 2026

Source: Authors' calculations based on the DAHITI water-level time series archived by Mammadov and Bernardino (2026).

The same variety of 11.597 m was observed in Shamkir Reservoir. The observations varied from 139.136 to 150.733 m, with a mean of 143.594 m and a most recent value of 147.293 m. Again, like Mingachevir, the extent of the range observed suggests that reservoir conditions may vary significantly from year to year. This variability is economically significant because it may impact the available storage, the generation potential for hydropower, the reliability of irrigation supply, downstream releases, and operational flexibility.

The elevation range of the Kura River was narrower than the elevation range of the reservoirs. Its observed values varied between 82.820 and 86.128 m, producing a range of 3.308 m and a mean of 84.157 m. The last one recorded was 84.161 m, virtually the same as the period mean. This indicates that the last value was not unusually high or low, when compared to the observed DAHITI record. However, the series of river-levels at any particular satellite target is indicative of local conditions of the water surface and not the full discharge response of the river basin. Therefore, it is recommended that the results are viewed as a hydrological indicator for a specific area.

The Araz River record ranged from 796.605 to 799.263 m, with a mean of 797.574 m. Its last observation was 798.826 m, which was above the period mean but was relatively close to the upper part of the range of observations. Elevation however, like the Kura River, cannot alone measure water availability, water flow volume or irrigation supply. Satellite-altimetry measurements are valuable to inform about surface-elevation dynamics, and must be interpreted in combination with discharge, precipitation, reservoir-operation and water-withdrawal data.

It is important to make a methodological distinction about uncertainty in measurement. Both reservoirs showed the mean reported uncertainty of about 0.009 m, and higher for the Kura and Araz rivers targets. The mean uncertainty was approximately 0.133 m and 0.075 m for the Kura river and Araz river respectively. This distinction is to be expected as the satellite-altimetry retrievals are typically more stable over large reservoir surfaces than small/relatively narrow/morphologically complex river channels. River measurements can be more sensitive to track location, the surrounding terrain, contamination of the waveform, and changing channel conditions.

The results show that combining the data from the reservoirs with the data from the rivers is not appropriate as a single hydrological trend. Operation decisions, storage rule, releases, energy demand, and irrigation demand have a high impact on the reservoir water levels. Water levels in rivers, on the other hand, are influenced by basin runoff, upstream regulation, seasonality, withdrawals, and local channel geometry. The present study, therefore, utilized these observations as individual water-level context indicators and did not compute a single national average.

From an economics point of view, the four systems have different, but related functions. The primary infrastructure for storage and regulation is located at Mingachevir and Shamkir, and the Kura and Araz rivers make up the backbone of Azerbaijan's surface-water system, serving the bulk of the country's irrigated agriculture. Variability in these systems can affect crop production and the generation of electricity as well as the health of downstream ecosystems and municipal use. In this case, although the 2017 observations may not be at historical lows, the recorded range suggests a high level of hydrological variability exists for water dependent economic activity.

The Caspian Sea analysis is complemented by the inland-water results. The Caspian series exhibited a consistent long-term decline while the selected inland systems exhibited fluctuations in time, depending on the water-management decision and natural processes occurred. This contrast further underscores the importance of an integrated assessment as Caspian coastal exposure is more closely related to long-term shoreline and water-level changes, whereas inland exposure is more related to regulated storage, river availability, irrigation dependence and regional water demands.

In the final index, the observations for inland water were therefore not considered a direct measurement of economic loss. Rather, they offered a hydrological perspective of the districts with connections to the selected reservoirs and river systems. This context is explored more directly in the following sections with the regional indicators of economic-exposure and agricultural water-dependency.

Economic Exposure of Caspian Coastal Regions

The economic-exposure assessment revealed that the population, industrial activity and capital investment are very unequally distributed among Azerbaijan's administrative units located in the Caspian coastal and near-coastal areas. Four indicators, namely total population, population density, industrial output and capital investment were combined and 2024 was used as a common reference year. These indicators were scaled and compiled into an Economic Exposure Index with a range of 0-100 (Mammadov, 2026c).

The main findings are given in Table 4. The index should be understood as a relative indicator of the density of economic resources that may be at risk for the long-term Caspian Sea level fluctuations. It does not calculate the likely extent of potential monetary damage or the risk of a particular coastal risk.

Baku had by far the highest index value (82.81). This is due to its very large population, large population density, outstanding capital investment and predominant industrial output. Among the selected group, Baku alone had an industrial output of about AZN 53.7 billion and capital investments of AZN 12.4 billion. As the country's capital, a key sea port city, industrial heartland and infrastructure center, it is the most vulnerable administrative unit in the assessment.

Sumgait was in second place with an index score of 31.94. It had only a minor part in the total population and investments compared with Baku, but Sumgait had the largest population density of the cities in the dataset, 3,563 persons per km2. It also boasted the second highest industrial production. These conditions reflect a high level of coastal exposure with a relatively small urban area with high concentrations of settlement, industry, transport and fixed infrastructure.

Absheron came in third, but with a score of 6.96 was much lower than Baku and Sumgait. Its exposure was mainly linked to population size, metropolitan expansion

Table 4: Economic exposure indicators for selected Caspian coastal regions of Azerbaijan, 2024

Region	Population, thousand persons	Population density, persons/km²	Industrial output, thousand AZN	Capital investment, thousand AZN	Economic Exposure Index
Baku	2,351.3	1,120	53,661,682.3	12,442,997.6	82.81
Sumgait	427.6	3,563	3,898,700.5	379,127.9	31.94
Absheron	434.0	206	991,685.0	340,154.2	6.96
Lankaran	228.1	148	167,474.2	59,330.9	3.40
Khachmaz	175.4	165	229,661.4	25,586.7	2.91
Astara	112.8	182	30,711.6	46,729.1	2.31
Salyan	140.3	88	139,872.1	110,613.6	2.13
Neftchala	87.6	60	82,917.0	18,373.3	1.15
Shabran	58.8	54	46,170.1	14,297.6	0.78
Siyazan	42.0	60	33,406.5	23,041.3	0.65
Khizy	16.8	10	11,696.2	47,320.4	0.07

Source: Authors' calculations based on official 2024 regional statistics archived in Mammadov (2026c).

and capital investment and not necessarily to a very high industrial output. These disparities between Absheron and the two main cities reflect high economic activity concentration along the coast in the Baku-Sumgait metro corridor.

The composite scores in the other areas were significantly lower. However, Lankaran, Khachmaz, Astara, Salyan and Neftchala are still relevant due to the differences in their exposure structures compared with the main industrial cities. Risk in these districts could be more related to tourism, agricultural, fisheries, border trade, local transport, wetlands, river and coastal/delta infrastructure. Some are of particular importance by virtue of their connection with the lower Kura River and the deltaic landscape, where the variability of the Caspian Sea and river conditions might interact.

Low scores in Shabran, Siyazan, and Khizy do not mean that these areas lack local vulnerabilities. This index is relative and greatly affected by the very high economic scale of Baku. A good national comparative score does not rule out that a district has locally significant shoreline change exposure if it has locally significant roads, settlements, tourism sites, agriculture, or other environmental assets.

These findings reiterate that it is important to distinguish between economic exposure and physical vulnerability. It does not take into account detailed coastal elevation, shoreline-retreat distance, port design, shoreline protection infrastructure, or asset-level sensitivity, and the index identifies where population and economic activity are concentrated. Thus, it is best to use the values for comparative screening and priority setting.

The high level of dominance in Baku and Sumgait suggests that the adaptation planning should be special emphasized in relation to the metropolitan Caspian corridor. Lower scoring coastal districts, however, should not be ruled out of policy consideration, particularly if local livelihoods are dependent on agriculture, fisheries, tourism, wetlands or river-delta systems. The analysis does not stop at the coastline, but continues to the regional level, considering the water dependency of agriculture in Azerbaijan.

Agricultural Water Dependency

It was revealed from the agricultural water-dependency assessment that exposure was mostly limited in districts that had high levels of crop production and high levels of irrigation-water use. The index was created by merging selected indicators of crop production with water abstraction, total consumption, irrigation and agricultural water use and water-loss pressure. Before aggregation, all variables were scaled as 0–100 (Mammadov, 2026a).

The top 10 districts are listed in Table 5. The outcomes should be viewed as relative dependency in Azerbaijan as

Table 5: Highest agricultural water-dependency scores in Azerbaijan, 2024

Rank	Region	Agricultural Water Dependency Index	Category	Water used for irrigation and agriculture, million m³	Selected crop production, tonnes	Crop-production dependency score
1	Agjabedi	56.83	Medium	477.4	457,085.5	34.61
2	Sabirabad	52.28	Medium	368.7	538,521.8	39.08
3	Shamkir	48.76	Medium	298.3	782,840.3	48.70
4	Saatly	48.04	Medium	347.9	324,756.8	28.40

5	Barda	46.55	Medium	425.6	345,249.7	24.56
6	Imishli	41.99	Medium	335.5	175,819.9	15.62
7	Goranboy	35.89	Medium	340.4	214,629.8	15.61
8	Kurdamir	32.44	Low	209.6	364,991.9	26.74
9	Salyan	32.15	Low	229.4	233,247.7	21.83
10	Beylagan	31.18	Low	251.2	211,354.4	17.79

opposed to as a measurement of absolute water scarcity.
The Agjabedi had the largest agricultural water-dependency score (56.83). This was mainly attributable to the irrigation and agricultural water use (477.4 million m³), which ranked among the top ten districts. The district also grew over 457 thousand tonnes of selected crops. This combination suggests a close link between crop production and irrigation water availability and provision.
Sabirabad was in the second place with 52.28 points. Selected crop production was more than 538 thousand tonnes and irrigation and agricultural water consumption was 368.7 million m³. This finding is in line with the district's geographical position in the Kura-Araz lowland with the irrigated crop production that is important in the economy of the region.
Although Shamkir used less irrigation water than Agjabedi, Sabirabad, Saatly, Barda, it ranked third. It was attributed to the biggest number of selected crop-production volume among the districts of the report, which was about 782.8 thousand tonnes. This shows that a district can be rated high in dependency due to the high intensity of water use, high agriculture production or both.
The localized areas of Saatly, Barda and Imishli also had high dependency scores. This is the group of districts that has large quantities of crop production and high consumption of irrigation water, over 300 million m³. The results they've reported suggest that altering how reservoirs are operated, the availability of the river, irrigation efficiency or conveyance losses can have economic impacts on local agriculture.
The index value for Goranboy was 35.89, which was the seventh. Even though several other districts had lower crop-production dependency scores, it had a high irrigation-water use of 340.4 million m³. This indicates that water use is relatively high compared to the chosen crop-production profile and that it is important to think about water intensity and not only production volume.
In the dataset, the districts of Kurdamir, Salyan and Beylagan were provided as low although they have been among the top ten districts. They are included to show that the thresholds for the categories were determined by the distribution of scores across all administrative units. A low category does not imply that agriculture is water independent, but rather that the district has a lower relative composite score than the top districts.
Results also indicate that water dependency in agriculture cannot be solely expressed by crop volume. Although Shamkir had the greatest volume of crop production, it was not the first thanks to the irrigation-water-use score, which was lower than Agjabedi. However, districts that were less productive could achieve dependency scores of higher value, even if irrigation use and the pressure for water losses were high. This is the validation of the incorporation of production and water-use variables in one composite indicator.
The loss of water is also a factor of pressure. If the amount of abstraction is significantly greater than the amount used, there is a significant amount of water that may be lost due to conveyance systems, canals, leakage, evaporation, or measurement inaccuracies. These losses lead to greater demand for water to maintain agricultural production, and diminish resilience when water supplies are low.
Agriculture is a major freshwater-consuming sector at the national level and the SDG 6.4 indicators indicate that water-use efficiency and water stress are development issues. National indicators are not included in the district-level rankings but are important for the interpretation of the district-level results (Mammadov, 2026g; UN-Water, n.d.-a, n.d.-b).
There is a clear link between inland water systems and regional economic exposure, as the higher dependency scores are concentrated in the central lowland and irrigated agriculture areas. These areas have an immediate and/or immediate dependent dependence on water from the Kura and Araz rivers, large reservoirs and on a wide-spread irrigation network. Rivers thus provide hydrological pressure which can be transferred to agricultural and economic risk due to variability in river level, storage condition and water-allocation efficiency.

Integrated Water Risk and Economic Exposure Index (IWREE)

In the last step of the analysis, all the aforementioned components were aggregated to the Integrated Water Risk and Economic Exposure Index, which includes the regional economic exposure, the agricultural water dependency, the water-level context and the national water-stress conditions. Scores of the result are indicative of the comparative assessment of the interaction between hydrological pressures and population and industry, investment, agriculture, and water-dependent activity spatial distribution across Azerbaijan (Mammadov, 2026e).
The index is not a probability of a particular disaster or the expected monetary value of future losses. Rather it identifies administrative units where current socio-economic exposure is relatively high in the context of the

observed long-term decline of the Caspian Sea, and the variability of strategic inland water systems.

The integrated score was highest in Baku (with 70.67). This was largely due to its high population density, industrial capacity, capital investments, urban infrastructure, and strategic coastal location. It differs from the leading agricultural districts, in the extent of its exposure, not being of an irrigation station character, but rather of an economic and coastal character. The outcome shows that Baku metropolitan area is the biggest one in terms of assets that may be impacted by long-term change in Caspian Sea.

Table 5: Economic exposure indicators for selected Caspian coastal regions of Azerbaijan, 2024

Rank	Region	Integrated index	Category	Main source of exposure
1	Baku	70.67	High	Coastal population, industry, investment and infrastructure
2	Agdjabadi	55.39	High	Irrigated agriculture and high agricultural water dependency
3	Sabirabad	52.66	High	Irrigation-intensive crop production and Kura–Araz dependence
4	Shamkir	50.54	High	Agricultural production and strategic reservoir dependence
5	Saatly	50.11	High	Irrigated agriculture and water-use intensity
6	Barda	48.53	Moderate	Agricultural production and irrigation demand
7	Imishli	46.01	Moderate	Kura–Araz lowland agriculture and water abstraction
8	Sumgait	44.87	Moderate	Coastal industrial concentration and high population density
9	Goranboy	42.55	Moderate	Agricultural water use and inland water dependence
10	Salyan	41.78	Moderate	Lower Kura, agriculture and near-coastal exposure

Source: Authors' calculations based on Mammadov (2026a–c, 2026e–g) and Mammadov and Bernardino (2026).

The next group of high scoring regions were Agjabedi, Sabirabad, Shamkir and Saatly. Their rankings were for the most part based on water dependency in agriculture as opposed to Baku. These districts are characterized by high concentration of irrigation-water use and dependence on Kura-Araz system and reservoirs as well as high level of crop production. They are showing that in Azerbaijan, the economic exposure to water is not restricted to the Caspian coastline only.

The second position was Agjabedi as it had the highest Agricultural Water Dependency Index. Sabirabad, Saatly, and Shamkir also exhibited high levels of irrigation, and significant production, whereas Shamkir had high agricultural production as well as strategic reliance on the Shamkir Reservoir and water-regulation structures.

Moderate category comprised Barda, Imishli, Sumgait, Goranboy and Salyan. Sumgait is of methodological importance due to the different structure of exposure within it as compared to the other regions in this group. Dense settlement and concentration of industries was the reason of its score, while in Barda, Imishli and Goranboy agricultural and irrigation indicators played the major role. Salyan's situation was intermediate, as it is an area that relies on agriculture and has low exposure to Kura and near-coast exposure. Figure 4 shows the spatial distribution of the final index.

The map below shows two main trends. The first is the high degree of economic concentration in the coastal location around Baku and Sumgait. The second is the high level of dependency of agriculture on water in the central lowland districts linked to the Kura-Araz river and irrigation system. This spatial contrast validates that national water risk has a variety of geographical aspects.

The map further shows that there are strategic water systems, which link together different regional exposure profiles. The water storage, hydropower, irrigation and regulation downstream of the Mingachevir and Shamkir reservoirs, and the main freshwater sources of many agriculturally dependent districts, are the Kura and Araz rivers. By contrast, the Caspian Sea has an impact on coastal settlement, infrastructure, industry, transport, wetlands and regional planning.

All these findings suggest that an integrated approach should be used. A coastal-only assessment would have missed Baku, Sumgait and underestimated the exposure of agriculture in the interior. In contrast, an irrigation-only assessment would show central agriculture regions, but it would not include the significant coastal economic assets. The combined index offers a better overall picture at the national level, viewing the coastal and inland water risks as interrelated and parts of a wider economic and environmental system.

However, caution must be used to interpret the results of the index. The scoring system is relative, and the final ranking depends on the indicators used and the normalization procedure and on the weighting structure. The weights have been calculated to make sure that district-level exposure is prioritized while also keeping the hydrological and national water-stress context. These rankings may vary if alternative weighting systems are used, especially for the regions that have similar scores.

The integrated approach is based on a methodological logic that is, more generally, followed in the construction of composite indicators, namely the integration of normalized variables to provide a representation of a multidimensional economic or environmental situation.

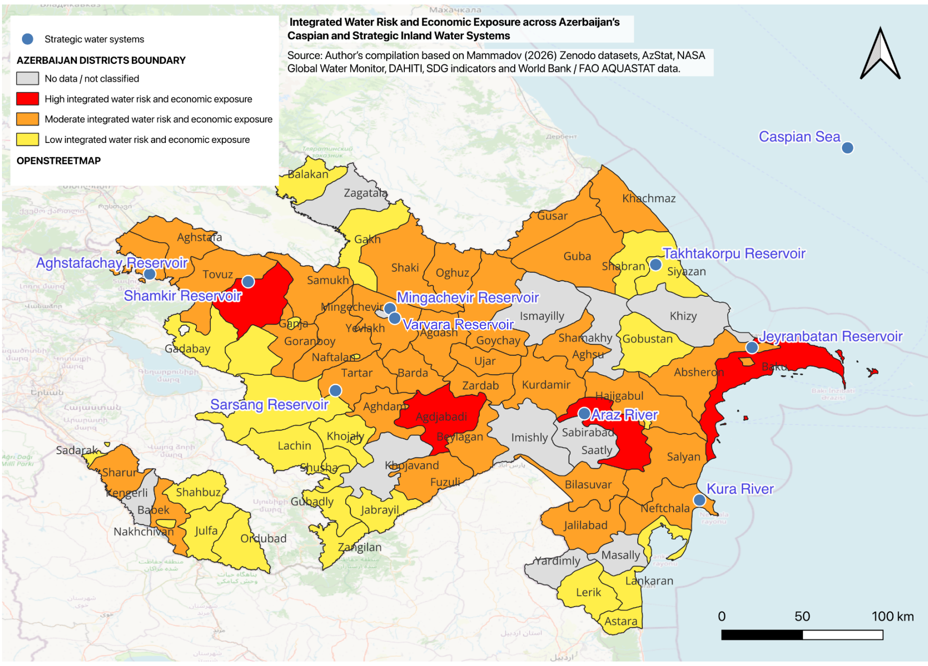

Figure 4: Integrated water risk and economic exposure across Azerbaijan's Caspian and strategic inland water systems. *Source: Mammadov (2026d), prepared in QGIS using the related Zenodo datasets, official regional statistics, NASA Global Water Monitor, DAHITI, SDG indicators, and World Bank–FAO AQUASTAT data.*

It has been shown that integrated indicators are also useful for the analysis of complex economic risks, such as in Azerbaijan, as shown by Guliyeva *et al.* (2021). This was extended to water-related environmental and socioeconomic exposure in the current study.

The results, in aggregate, lead to the conclusion that water-risk policy should be targeted to three priority groups:

- main urban and industrial centres along the coast;
- irrigation-dependent agricultural districts;
- Strategically linked regions to reservoirs and rivers.

These groups need differential policy response, as outlined below.

The spatial patterns identified by the index suggest differentiated policy priorities. Coastal urban and industrial centres require climate-sensitive infrastructure and land-use planning, while irrigation-dependent districts require canal rehabilitation, water-loss reduction, digital metering, and improved reservoir coordination. Green finance instruments may support investments in monitoring, irrigation modernization, storage, and climate-resilient infrastructure.

CONCLUSION

The main objectives of this study were to evaluate water-level variability and economic exposure in Azerbaijan using the satellite altimetry data with the official regional statistics, national water indicators, and spatial analysis with the use of QGIS. The results showed that the water level of the Caspian Sea has been decreasing in the long-term and the variability of the water level has been observed in the Mingachevir and Shamkir reservoirs and the Kura and Araz rivers at the target points. Two predominant spatial patterns were identified in the Integrated Water Risk and Economic Exposure Index. High exposure to coastal urban-industrial pollution marked Baku and Sumgait, while Agjabedi, Sabirabad, Shamkir and Saatly were mostly impacted by the agricultural dependency on water and the strategic inland water systems. These findings show the need to consider jointly water related risk in coastal and inland areas of Azerbaijan. The proposed index is a comparative screening index and not a formal hazard classification. It is the combination of hydrological, economic, agricultural, and water-stress indicators in a transparent and reproducible framework that is its primary contribution. Findings can be used for coastal planning, irrigation modernization, reservoir coordination, water-loss reduction and climate-resilient investment. The socio-economic reference year for the study is only 2024 and there are various differences in the water body coverage of the satellites. Multi-year regional statistics, shoreline-change analysis, exposure at the infrastructure level and other index-weighting scenarios are suggested for future research.

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