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Forty-Year (1986-2025) Monitoring of Gorgan Bay Surface Area and Its Relationship with Caspian Sea Level Fluctuations

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ABSTRACT

Aims In light of the alarming desiccation trend of Gorgan Bay, the primary objective of this research is to conduct long-term monitoring of the bay's water surface area changes over a 40-year period (1986-2025) and to investigate the determining roles of Caspian Sea level (CSL) oscillations and precipitation in the Qarasu watershed on these morphological variations.

Methodology This study utilized a time series of 36 Landsat satellite images. For precise water body extraction, the Modified Normalized Difference Water Index was applied. To evaluate the accuracy of the area results, a classification map was generated from a Sentinel-2 image using the Support Vector Machine method, followed by error matrix calculations. Water level data were retrieved and harmonized by integrating Baku station records with the DAHITI database. Additionally, precipitation data for the Qarasu basin were obtained from the CHIRPS database. Statistical analyses were performed using the Pearson correlation coefficient.

Findings The area of Gorgan Bay decreased from a maximum of 565.48km2 in 1995 to a minimum of 275.12km2 in 2023, indicating a loss of more than 50% of its peak area. The area of Gorgan Bay was significantly positively correlated with the level of the Caspian Sea ($p<0.001$; $r=0.9419$), but not with the rainfall of the basin ($p=0.2142$; $r=0.2121$).

Conclusion As a semi-closed ecosystem, Gorgan Bay is subject to the hydrodynamic regime of the Caspian Sea and, due to the gentle slope of the bed, acts as a sensitive indicator of sea level changes. Local precipitation in the catchment area cannot compensate for the coastline's retreat caused by a fall in the Caspian Sea level.

Keywords Gorgan Bay; Caspian Sea Level; Remote Sensing; Landsat; Modified Normalized Difference Water Index

CITATION LINKS

[Aghighi *et al.*, 2009] Estimation of water turbidity in Gorgan Bay ...; [Amiri *et al.*, 2021] Study and monitoring of wetland area changes and its ...; [Behzadnia & Dorbeiki, 2020] Carrying capacity of nature-tourism in Ashooradeh Island ...; [Climate Hazards Center, University of California Santa Barbara (UCSB), n.d.] CHIRPS data (Climate Hazards Group Infrared Precipitation ...; [Deutsches Geodätisches Forschungsinstitut, Technical University of Munich (DGFI-TUM), n.d.] DAHITI-Database for Hydrological Time ...; [Ebadi, 2022] Optimum method for water body ...; [European Space Agency, n.d.] Copernicus Sentinel-2 data collection ...; [Gharibreza *et al.*, 2018] Evolutionary trend of the Gorgan Bay (southeastern Caspian Sea) during ...; [Ghayoumi, 2017] Environmental challenges of Gorgan Bay and Miankaleh Wetland and providing ...; [Hamzeh & Torabi, 2021] Investigating the changes in the water body of Gorgan Bay and ...; [Jafari *et al.*, 2021] Investigation of flow pattern in Gorgan Gulf considering ...; [Khoshravan, 2018] Fluctuations in the Caspian Sea's water ...; [Khoshravan & Rohanizadeh, 2021] Rapid fluctuations in the water level of the ...; [Mansouri & Sarbazi, 2017] Study of changes and developments in Gorgan Bay during ...; [McFeeters, 1996] The use of the Normalized Difference Water ...; [Parsaee & Mofidi Khajeh, 2009] Management of the Gorgan Bay ...; [Pourimani *et al.*, 2023] Absorption dose distribution pattern and radiological ...; [Rahimi *et al.*, 2019] Miankaleh Peninsula coastline changes ...; [Sabaee *et al.*, 2011] Caspian Sea level fluctuation and ...; [Sharbaty, 2019] Investigation of locating a new communication channel in the Gorgan ...; [Sharbaty, 2023] Investigation of the Caspian Sea water level decreasing effects ...; [Sharbaty & Ghanghermeh, 2016] Forecasting the effect of decreasing long ...; [Sharbaty & Nasimi, 2018] Modeling of possible dredging effects of Khozeini channel on the ...; [Shayan *et al.*, 2013] Detection of changing the northern coastline using RS and GIS ...; [U.S. Geological Survey, n.d.] Earth Explorer ...; [Xu, 2006] Modification of normalised difference water index (NDWI) to enhance ...; [Yousefi Roshan, 2015] Caspian Sea water level fluctuations during the instrumental recording period from ...;

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Introduction

Gorgan Bay, as the largest bay of the Caspian Sea, is one of the most vital coastal ecosystems of Iran and a semi-enclosed sedimentary environment [Gharibreza *et al.*, 2018; Khoshravan & Rohanizadeh, 2021; Ghayoumi, 2017; Hamzeh & Torabi, 2021; Parsaee & Mofidi Khajeh, 2009]. Owing to its ideal biological conditions, this basin is the natural habitat of diverse animal species and is known as the main nursery of many juvenile fish and a safe place for the reproduction and wintering of waterbirds in the southern part of the Caspian Sea [Gharibreza *et al.*, 2018; Ghayoumi, 2017]. From an economic perspective, Ashooradeh Island at the entrance of this bay has enjoyed international fame as an advanced national center in the fishing and caviar production industry, and its natural attractions and wildlife have created unique tourism potential [Gharibreza *et al.*, 2018; Parsaee & Mofidi Khajeh, 2009; Ghayoumi, 2017; Behzadnia & Dorbeiki, 2020].

Nevertheless, the direct hydrological connection of this bay with the Caspian Sea and the Miankaleh Wetland has turned it into a highly sensitive and dynamic system whose stability depends directly on sea-level fluctuations [Hamzeh & Torabi, 2021; Sharbaty, 2019]. In recent years, the declining trend of the Caspian Sea level (more than 120 centimeters over the past 20 years) has led to severe shoreline retreat and desiccation over large parts of the bay [Hamzeh & Torabi, 2021; Khoshravan & Rohanizadeh, 2021]. This phenomenon has not only sharply reduced the water-body area but, by accelerating the process of ecological succession, has also turned aquatic environments into mudflats and dry lands [Khoshravan & Rohanizadeh, 2021; Ghayoumi, 2017]. In addition to sea-level fluctuations, the climatic variables of the catchment also play a decisive role in the hydrological balance of the bay. Since the Gharesu River is the main source of fresh water for Gorgan Bay, changes in precipitation in this basin can affect the inflow discharge and, consequently, fluctuations in the water-body area at short-term scales [Hamzeh & Torabi, 2021; Pourimani *et al.*, 2023]. Therefore, the simultaneous analysis of the effects of Caspian Sea level fluctuations and the precipitation of the Gharesu catchment on changes in the area of Gorgan Bay is a key issue for predicting the future of this ecosystem and formulating management strategies to prevent its complete destruction.

Hence, continuous and accurate monitoring of the morphological and water-body changes of Gorgan Bay is of vital importance owing to the dynamic nature and high sensitivity of this ecosystem to environmental fluctuations [Shayan *et al.*, 2013; Rahimi *et al.*, 2019; Ghayoumi, 2017]. In this regard, remote sensing technology, owing to features such as a wide view, repeatability, low cost, and high accuracy, is recognized as an indispensable tool for continuous monitoring of shoreline changes and optimal management of sensitive areas [Rahimi *et al.*, 2019; Khoshravan & Rohanizadeh, 2021]. In particular, Landsat satellite imagery, by providing a valuable historical archive from the 1970s to the present, makes it possible to accurately analyze the temporal trends of changes in water bodies and provides important baseline information for natural resource management and large-scale environmental planning [Mansouri & Sarbazi, 2017; Hamzeh & Torabi, 2021; Rahimi *et al.*, 2019].

Therefore, the aim of the present study is to monitor and analyze changes in the area of Gorgan Bay over a long-term period using a time series of Landsat satellite images and digital processing techniques. In this regard, an attempt has been made, while detecting the changes and identifying the temporal trends governing this water body, to examine the role of key factors, especially fluctuations in the Caspian Sea water level, which according to previous studies has a very high correlation with changes in the area of the bay.

Extensive research has shown that, owing to its shallow depth and very gentle bed slope, Gorgan Bay reacts strongly to changes in the Caspian Sea water level [Sharbaty & Ghanghermeh, 2016; Mansouri & Sarbazi, 2017]. A study of a twenty-year time series (1999–2019) showed a very high correlation (92%) between changes in the water-body area of the bay and Caspian Sea level fluctuations [Hamzeh & Torabi, 2021]. According to the findings of that study, while the sea level decreased by about 120 centimeters during this period, the area of the bay followed a similar downward trend. In contrast, the correlation of the water-body area with precipitation was estimated to be very small (about 10%) on a long-term scale. However, in short-term and seasonal analyses, the effect of precipitation on the area of the bay is evident with a one-month time lag, such that the maximum water-body area is usually observed one month after peak precipitation.

In other historical studies, researchers examining four periods between 1955 and 2011 found that the area of the bay reached its highest value (518 square kilometers) in 2005 and its lowest value (403 square kilometers) in 1955, which was directly related to the sea level in those years [Shayan *et al.*, 2013]. Another study reported that, in 2014 alone, a 12-centimeter decrease in water level led to a reduction of about 48 square kilometers in the water-body area of the bay [Yousefi Roshan, 2015]. In a study in 2017, researchers emphasized that, following recent recessions, about 35% of the extent of Gorgan Bay and large parts of the northeast of the Miankaleh Wetland have dried up and turned into mudflats [Mansouri & Sarbazi, 2017].

The use of remote sensing technology, owing to its wide coverage, high frequency, and free access, is recognized as an efficient method for monitoring changes in the shorelines and water bodies of Gorgan Bay [Rahimi *et al.*, 2019; Khoshravan & Rohanizadeh, 2021]. Various studies have used images from different satellites, including Landsat, Sentinel-2, and IRS-LISS-III [Aghighi *et al.*, 2009; Hamzeh & Torabi, 2021].

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Extracting water bodies from satellite images is one of the important applications of remote sensing in environmental and water resources studies. Numerous methods have been developed in this field, each with its own advantages and limitations. One of the most common approaches is the use of classification methods, such as supervised and unsupervised classification, which separate different classes, including water and land, based on the spectral characteristics of pixels. Although these methods are accurate in many cases, they depend on training data and parameter tuning, are time-consuming, and may not perform well in complex areas.

Another method is to exploit the high absorption of water in the near-infrared (NIR) spectrum and to threshold band 5 of Landsat (in the TM and ETM+ sensors) to distinguish land from sea [Shayan *et al.*, 2013]. In previous research, band subtraction and density slicing methods have also been used to detect shoreline changes in Miankaleh and Gorgan Bay [Rahimi *et al.*, 2019].

In many sources, spectral indices have been widely used as a simple, fast, and efficient method for extracting water bodies. The Normalized Difference Water Index (NDWI) is one of the first indices in this field, which uses the green and near-infrared bands to separate water from other land uses [McFeeters, 1996]. However, this index is prone to errors in some cases, especially in urban areas or areas with dense vegetation. To improve the performance of NDWI, a modified index called the Modified Normalized Difference Water Index (MNDWI) was introduced, in which the shortwave infrared (SWIR) band is used instead of the near-infrared band [Xu, 2006]. This change increases the accuracy of separating water bodies, especially in areas with background noise such as urban land and moist soils. In addition, combining spectral indices with thresholding methods and multitemporal analysis has made more accurate monitoring of changes in water bodies possible and is recognized as an effective approach in environmental change studies.

In a study aimed at monitoring changes in the area of the Hoor-Al-Azim and Shadegan wetlands, the efficiency of different spectral indices was evaluated [Amiri *et al.*, 2021]. The findings of that study showed that MNDWI performs far better than NDWI and the Automatic Water Extraction Index (AWEI) in separating water bodies from complex coastal and wetland environments. These researchers emphasized that MNDWI, by using the shortwave infrared band, is more successful in removing noise caused by the mixing of water pixels with vegetation and moist soils and shows higher repeatability in extracting water-body areas from Landsat images. MNDWI has also been used to extract the water body of Gorgan Bay, and its superiority over NDWI in separating water from complex coastal environments has been confirmed [Hamzeh & Torabi, 2021]. A review of previous studies shows that MNDWI, owing to its ability to separate the water body from complex coastal environments and its high speed, is a suitable tool for monitoring the fluctuations of Gorgan Bay [Hamzeh & Torabi, 2021; Ebadi, 2022]. However, an examination of the scientific literature reveals two main gaps in research in this field: a lack of temporal continuity (most previous studies have focused on discrete time periods or intervals of 10 to 20 years, an approach that precludes accurate analysis of annual trends and the identification of momentary and intermediate fluctuations in the area of the bay) [Shayan *et al.*, 2013; Rahimi *et al.*, 2019; Hamzeh & Torabi, 2021], and a shortage of long-term quantitative analyses (despite the proven influence of the Caspian Sea level on the bay, most studies have focused on qualitative analyses, hydrodynamic modeling, or the effects of dredging, and quantified statistical analyses that extract the mathematical correlation between area and sea level over a coherent, multi-decadal time course remain limited) [Sharbaty & Nasimi, 2018; Sharbaty, 2019; Hamzeh & Torabi, 2021].

Accordingly, the main aim of the present study was to fill these scientific gaps through continuous, annual monitoring of the water-body area of Gorgan Bay over a period of nearly 40 years (1986 to 2025) using Landsat images.

Methodology

The present study is applied research based on a case study, in which the general framework relied on quantitative methods, image processing, and statistical analyses. The study area is Gorgan Bay, the largest bay of the Caspian Sea, located at the southeastern extremity of this sea between longitudes 53°25′ and 54°06′ E and latitudes 36°46′ and 37°00′ N (Figure 1).



Figure 1) Study area

Its area has been reported in various sources as between 400 and 550 square kilometers, its maximum length as about 60 to 70 kilometers, and its width as between 12 and 14 kilometers. Hydromorphologically, Gorgan Bay is a very shallow basin with an average depth of less than 2 meters. The maximum depth of the bay, about 4.5 to 5 meters, has been recorded in its eastern parts near the entrance mouth; this value gradually decreases westward owing to the high rate of fluvial sedimentation and the reduced effect of exchange with the sea, reaching zero on the western shores. Bandar Torkaman, the most important navigation port of the region, is located 5 kilometers from the entrance channel in the northeastern corner of the bay's shore. The bay exchanges water with the Caspian Sea through

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the Ashooradeh (Chapoghli) and Khazini connecting channels, which ensure its hydrological dynamics [Sharbaty & Nasimi, 2018; Sharbaty, 2019; Gharibreza *et al.*, 2018; Mansouri & Sarbazi, 2017; Ghayoumi, 2017; Khoshravan & Rohanizadeh, 2021].

For continuous monitoring of changes in the water-body area over a period of nearly 40 years (1986 to 2025), 36 Landsat spectral images, including the TM, ETM+, and OLI sensors, with path 163 and row 34, mostly in summer (owing to the stability of atmospheric conditions and minimal cloud cover), were obtained from the Earth Explorer database. In a few cases, owing to gaps in the archive, the nearest good-quality image from other months was used [U.S. Geological Survey, n.d.].

For accurate detection of water boundaries in images at processing Level 2 with the necessary corrections, MNDWI, combining the green and shortwave infrared (SWIR) bands (Formula 1), was applied to remove environmental noise (vegetation and moist soils).

Formula 1)

$$\text{MNDWI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}$$

Processing was carried out in ENVI 5.6 by applying a zero threshold to the histogram of MNDWI images to produce binary (water and non-water) maps; the layers were then transferred to ArcGIS 10.8.2 to calculate the area, and finally, to resolve the striping problem in Landsat 7 images (black, no-data lines), the polygon geometries were reviewed and refined in AutoCAD.

Caspian Sea water-level data for the period from 1993 onward were obtained from the DAHITI database (derived from altimetry missions such as Jason and TOPEX/Poseidon), and for the years 1986 to 1992 they were obtained by extracting data from the fluctuation charts of the Baku station [Saeed Sabaee *et al.*, 2011; DGFI-TUM, n.d.]. To validate and ensure the continuity of the water-level data over the 40-year research period, the values extracted from the DAHITI database were compared with instrumental records [Saeed Sabaee *et al.*, 2011] in the overlapping period (years with Landsat images between 1993 and 2000). The results showed that the mean level in the DAHITI data (−26.22 m) agrees very closely with the corresponding mean in the fluctuation curve of the Baku tide-gauge station (−26.23 m). This maximal closeness of the means in the common period proves that both data sources follow the same height datum (the Baltic Sea datum). Therefore, to preserve the originality of the data, there was no need to apply a correction coefficient or an additional harmonization process. This made it possible to create an integrated time series free of systematic error for the entire research period, so that correlation analyses between sea level and the area of the bay could be performed with high confidence.

To examine climatic effects, cumulative precipitation data were retrieved from the CHIRPS database [Climate Hazards Center, n.d.]. The six-month cumulative precipitation ending in the month of image acquisition (based on the hypothesis of a time lag in the response of the bay) was extracted, and the precipitation raster layers were clipped and averaged in ArcGIS based on the geographical boundary of the Gharesu catchment, as the main source of fresh water for the bay.

To assess the validity of the extracted areas, a Sentinel-2 satellite image with a spatial resolution of 10 meters and the support vector machine (SVM) classification method were used [European Space Agency, n.d.]. The Landsat series was chosen for the 40-year monitoring instead of Sentinel because of the absence of a Sentinel historical archive in the 1980s and 1990s. In addition, MNDWI was preferred to classification methods because, in addition to its high processing speed for long time series, this index works on the basis of the physical reflectance of features and, unlike classification methods, is free of bias and human error in the selection of training samples.

Findings

The characteristics of the satellite images, the sea water level, and the precipitation of the catchment are presented in Table 1.

According to the calculations, the extent of the bay experienced severe fluctuations over these four decades, which could be classified into four distinct periods (Chart 1).

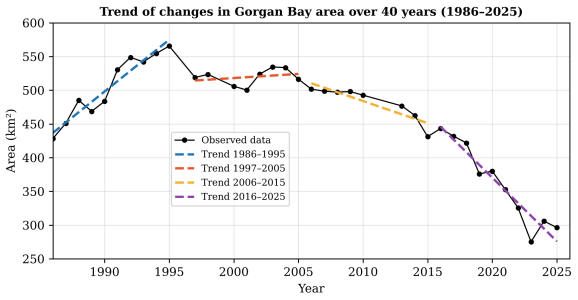

Chart 1) Temporal changes in the area of Gorgan Bay along with its change trends

In the first period, which lasted from 1986 to 1995, the area of the bay had an increasing trend and reached its maximum, 565.48 square kilometers, in 1995. This increase in extent fully coincided with the period of the Caspian Sea transgression in those years. In the second period, between 1997 and 2010, the extent of the bay remained stable at around 500 square kilometers and showed limited fluctuations.

The third period, which began in 2013 and continued until 2025, was a time of severe and alarming decline in the extent of the bay. During this period, the water body shrank rapidly and reached its lowest historical value of 275.12 square kilometers in 2023, showing that the bay had lost more than half of its extent at its peak. Finally, in

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Table 1) Results obtained for the area of Gorgan Bay, the Caspian Sea water level, and the six-month cumulative precipitation

No.	Satellite	Acquisition date	Solar year	Area of Gorgan Bay (km^2)	Caspian Sea water level (m)	Six-month cumulative precipitation (mm)
1	Landsat 5	1986/08/14	1365	428.2214	−27.4	225.6111
2	Landsat 5	1987/06/14	1366	450.9828	−27.3	367.3342
3	Landsat 5	1988/12/25	1367	484.8759	−27.2	280.3623
4	Landsat 5	1989/05/02	1368	468.6390	−27.1	276.3357
5	Landsat 5	1990/08/25	1369	483.4922	−27.0	130.5690
6	Landsat 5	1991/06/25	1370	530.3691	−26.8	370.0331
7	Landsat 5	1992/06/11	1371	548.7348	−26.7	448.4247
8	Landsat 5	1993/06/14	1372	541.9206	−26.236	343.3534
9	Landsat 5	1994/07/03	1373	554.5070	−26.034	210.3152
10	Landsat 5	1995/06/20	1374	565.4795	−25.876	213.6530
11	Landsat 5	1997/05/08	1376	518.8868	−26.459	264.8843
12	Landsat 5	1998/04/09	1377	523.3521	−26.446	419.1522
13	Landsat 5	2000/07/19	1379	505.8621	−26.302	157.2663
14	Landsat 5	2001/09/08	1380	500.1247	−26.641	131.4633
15	Landsat 5	2002/06/23	1381	523.8345	−26.403	305.4626
16	Landsat 7	2003/08/05	1382	534.4588	−26.406	306.4970
17	Landsat 7	2004/06/04	1383	533.4434	−26.237	343.5197
18	Landsat 7	2005/07/25	1384	516.3566	−26.118	285.1092
19	Landsat 7	2006/06/10	1385	501.5754	−26.263	292.1299
20	Landsat 7	2007/07/15	1386	498.5129	−26.382	343.6914
21	Landsat 7	2008/06/15	1387	497.1825	−26.558	220.5495
22	Landsat 5	2009/06/26	1388	497.9740	−26.496	377.6291
23	Landsat 5	2010/06/13	1389	492.5643	−26.502	444.9768
24	Landsat 8	2013/07/07	1392	476.6924	−26.828	265.8253
25	Landsat 8	2014/07/26	1393	462.5912	−27.076	265.9269
26	Landsat 8	2015/07/29	1394	431.0712	−27.27	228.2979
27	Landsat 8	2016/06/29	1395	443.1769	−27.157	392.9641
28	Landsat 8	2017/07/18	1396	431.7845	−27.282	203.0046
29	Landsat 8	2018/07/05	1397	421.8168	−27.243	244.0616
30	Landsat 8	2019/06/22	1398	375.7293	−27.5	578.4945
31	Landsat 8	2020/06/08	1399	379.9599	−27.428	308.0045
32	Landsat 8	2021/06/27	1400	352.7225	−27.626	243.1682
33	Landsat 9	2022/06/06	1401	325.4714	−27.844	250.4748
34	Landsat 8	2023/08/12	1402	275.1257	−28.167	208.7140
35	Landsat 9	2024/07/05	1403	305.8358	−28.175	206.6733
36	Landsat 9	2025/07/16	1404	296.1580	−28.382	133.3600

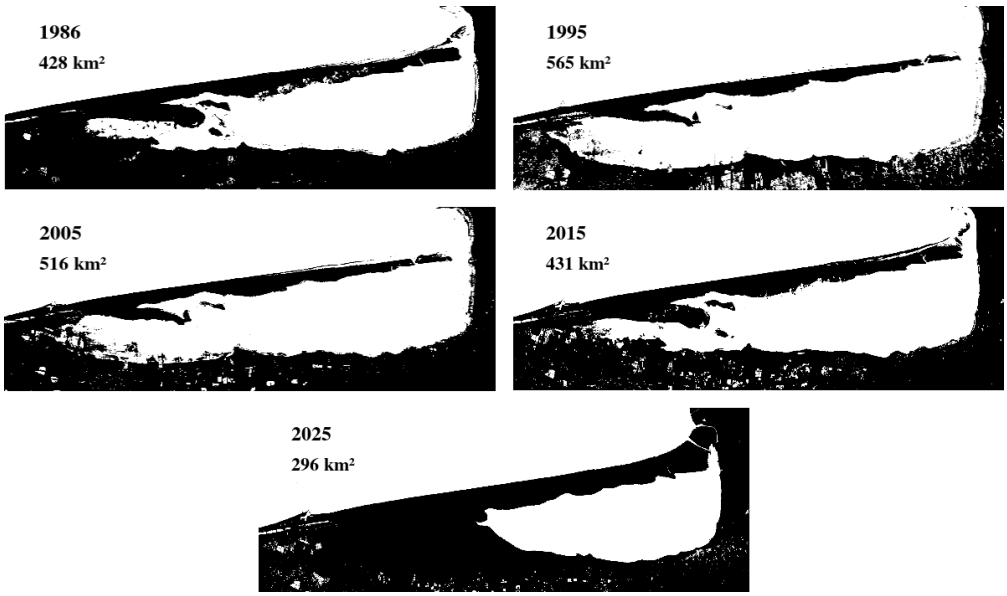

Figure 2) Water body of Gorgan Bay at intervals over the forty years from 1986 to 2025 (using MNDWI on Landsat images)

the last two years (2024 and 2025), a very slight recovery in area was observed, and the extent of the bay reached about 300 square kilometers. The images extracted at ten-year intervals (Figure 2) clearly showed the trend of water bodies turning into dry land on the western and southern fronts.

The scatter plot obtained from the Pearson correlation between the Caspian Sea water level and the water-body area of Gorgan Bay over the 40-year research period showed that, as the sea level decreased, the area of the bay shrank with very high sensitivity and followed a downward trend. The results confirmed the existence of a positive, direct, and strong correlation ($r = 0.9419$) between these two variables. More than 88% of the changes in the extent of Gorgan Bay over the past four decades (1986 to 2025) were directly explained by Caspian Sea level fluctuations. This significant correlation reflected the direct and close hydraulic connection between the water body of Gorgan Bay and the Caspian Sea through the connecting channels (such

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as Ashooradeh and Chapoghli) (Chart 2).

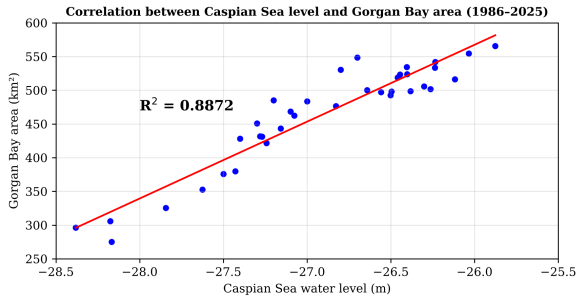

Chart 2) Correlation between the area of Gorgan Bay and the Caspian Sea water level

The retreat of the shoreline in the shallow western areas fully matched the decline in sea level. In contrast, examination of the precipitation of the Gharesu catchment showed that fluctuations in cumulative precipitation had no decisive effect on changes in the extent of the bay on a long-term scale, and no relationship between the two was observed (Figure 3).



Figure 3) Overlay map of shoreline fluctuations of Gorgan Bay over the past four decades (1986–2025)

The six-month cumulative precipitation of the Gharesu catchment had no significant correlation with the water-body area of Gorgan Bay ($r = 0.2121$; $p = 0.2142$).

The results of the error matrix showed an agreement of 99.76% (kappa coefficient of 0.996) between the map extracted with MNDWI and the SVM reference map. In addition, a quantitative comparison of the areas showed that the extent of the bay was 352.7225 square kilometers in the Landsat image and 358.2108 square kilometers in the Sentinel reference image, so their relative difference was about 1.5%. This difference was mainly concentrated in the shallow and muddy western areas of the bay, where, owing to mixed pixels and spectral ambiguity, accurate separation of the water–land boundary was more challenging. In the remaining areas, the two sources showed high geometric agreement in water boundaries (Figure 4).

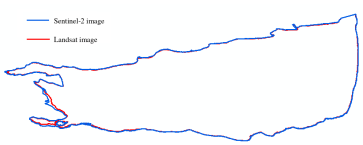

Figure 4) Extent of Gorgan Bay in 2021 extracted from Landsat and Sentinel-2 images

Discussion

The main aim of this study was the continuous, forty-year monitoring of fluctuations in the water-body area of Gorgan Bay (1986 to 2025) and the examination of the decisive contribution of Caspian Sea level fluctuations and the precipitation of the Gharesu catchment to the morphological evolution of this sensitive ecosystem. The findings of this study showed that Gorgan Bay lost more than 50% of its extent during the study period, decreasing from 565.48 square kilometers in 1995 to 275.12 square kilometers in 2023. This rate of area reduction is far beyond the 30–35% figures reported in previous studies [Khoshravan & Rohanizadeh, 2021; Mansouri & Sarbazi, 2017], indicating the acceleration of the desiccation process in the last decade and the entry of the bay into a critical phase. According to the new findings, the continuation of the declining water-level trend has not only led to the shrinkage of the water body but, by disrupting the biological balance, has seriously threatened the life of the bay's native species [Sharbaty, 2023]. Also, in line with the scenarios proposed by Khoshravan [Khoshravan, 2018], this declining level is driving Gorgan Bay toward complete desiccation and conversion into mudflats, a phenomenon clearly observed in this study in the severe shrinkage of the western front of the bay.

The 94% correlation between sea level and the area of the bay in this study strongly supports the hypothesis of the absolute dominance of the Caspian hydrodynamic regime over the geometry of the bay. This result is consistent with the findings of previous studies that reported a 92% correlation over a 20-year period and proves that, on a forty-year scale as well, sea level is the governing variable [Hamzeh & Torabi, 2021]. This strong physical dependence is due to the very shallow depth and extremely gentle bed slope of the bay, which have turned it into a sensitive indicator of the Caspian Sea level. In confirmation of this, Jafari *et al.* [Jafari *et al.*, 2021], using numerical modeling, showed that changes in the Caspian Sea water level directly affect the pattern of currents and water circulation inside the bay. In other words, the decline in sea level not only reduces the water-body area but, by changing the hydrodynamic structure, reduces water exchange between the bay and the sea and disrupts the self-purification process. This finding is consistent with the visual observations of this research regarding the blockage of the Ashooradeh and Chapoghli connecting channels.

In contrast, the lack of a significant relationship between the precipitation of the Gharesu catchment and the area of the bay shows that atmospheric inputs and local river flows are unable to compensate for the water retreat caused by the decline in the Caspian Sea level. This result is fully consistent with the findings of Hamzeh and Torabi [Hamzeh & Torabi, 2021], who reported a very small long-term correlation with precipitation. The interpretation of this phenomenon is that Gorgan Bay is controlled by the water budget of the Caspian

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Sea rather than by the freshwater budget of its own catchment. Therefore, even in years when precipitation in the Gharesu catchment was normal or above normal, the retreat of the bay did not stop because of the cumulative decline in the Caspian level. According to the analyses of Sharbaty [Sharbaty, 2023], the reduction in depth caused by the falling level has also increased the sensitivity of the bay to evaporation and accelerated the process of ecological succession. The images extracted in this study also revealed the blockage of the connecting channels; Khoshravan [Khoshravan, 2018] believes that the closure of the connecting mouth due to severe sedimentation has created the conditions for ecological succession and is driving the aquatic ecosystem toward becoming dead wetlands and ultimately dry land. According to the results of this study, the lateral displacement of the shoreline in some western points has reached several kilometers, which confirms scientific warnings about the imminent collapse of life in the bay. The complete blockage of the Khazini channel and the severe narrowing of the Ashooradeh (Chapoghli) mouth, which had been raised in previous studies as an alarm for the disconnection of the bay's hydraulic connection, are clearly evident in the visual results of this study up to 2025 [Sharbaty & Nasimi, 2018; Sharbaty, 2019]. The advance of the Miankaleh sand spit at an average rate of 68 meters per year, observed at some points in this study, is consistent with the findings of previous research and confirms the process of ecological succession and the conversion of the aquatic ecosystem into mudflats and dry land [Khoshravan & Rohanizadeh, 2021].

Gaps in satellite data in the early 1990s due to technical problems of the Landsat 7 sensor, as well as difficulty in accessing accurate statistics on human withdrawals from river water rights, were among the main limitations of this study in analyzing more precisely the contribution of freshwater sources. Given the 94% dependence of changes in the extent of the bay on sea level, adopting environmental adaptation policies instead of purely structural interventions is recommended. However, to prevent complete hydraulic blockage, dredging of the Ashooradeh mouth and examining the possibility of constructing new channels, such as the Anzan channel in the deepest part of the bay, to improve self-purification and water renewal could be a priority of conservation programs. In addition, controlling soil erosion upstream in the Gharesu catchment to reduce the incoming sediment load and preserve the remaining depth of the bay is an unavoidable necessity.

Conclusion

Gorgan Bay, as a semi-enclosed ecosystem, is subject to the hydrodynamic regime of the Caspian Sea and, owing to its gentle bed slope, acts as a sensitive indicator of changes in sea level. Local precipitation in the catchment cannot compensate for the shoreline retreat caused by the decline in the Caspian Sea level.

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