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Evaluating the effects of Caspian Sea water level fluctuations on the coast morphodymanics (Case study of Spit Miankaleh and Gorgan River delta)

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A B S T R A C T

The changes in the water level of the Caspian Sea cause many problems in the field of sustainable development of the coasts of this lake. The Caspian Sea water level fluctuations are severe and has varied between -25 and -29 meters between 1880-2023. The short and long-term planning of the countries along this lake depends on comprehensive understanding the effects of these water level fluctuations on the coasts, and any planning to achieve the desired regional goals will fail without paying attention to these processes. The aims of this research are evaluating the effect of sea level fluctuations on the Iranian eastern coasts of the Caspian Sea from Amirabad to the Gorgan River delta and to determine the vulnerable areas of the coasts and also assessed the effect of these fluctuations on the hydrodynamics of waves. Hence coastlines extracted from Landsat data in four time periods of 1975, 1998, 2011 and 2023, besides DSAS system was used to quantitatively evaluate the rate of changes in coastlines. Also, MIKE21 software and sea buoy data were used to investigate the effect of sea level fluctuations on wave parameters. The results indicate that the mouth of Gorgan Bay and the Gorgan River delta where the most unstable parts of the coastline and are highly sensitive to sea level fluctuations. Between 1975 and 2023 more than 4600m coastline changes observed in this region, especially in the Gorgan Bay mouth. In addition, the results of the modeling of wave in high and low water table show that the wave height has increased simultaneously with the rise of the sea level, and the maximum wave height has increased from 1.3 meters in 1975 to 1.6 meters in 1998, this increase in wave height besides submergence of coastal areas can intensified the process of erosion in the coastal zone.

A R T I C L E I N F O

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1. Introduction

The coastline, is defined as the physical interface between land and water. The International Committee of Geography has considered coastal areas as the most unique natural areas. The coastal areas are valuable due to having sensitive ecosystems (Kuroshinia, 2010). Coastal and marine process certain consequences in the human-economic and environmental dimensions, which understanding and recognition of this process can be an efficient tool in coastal management (Khan Mohammadi et al., 2019) Besides coastal areas are constantly changing physically and ecologically under the influence of natural and human factors. These changes have affected the coastline and coastal areas and have a negative effect on human life, human activities and the marine environment. Monitoring the coastal area is an important issue in coastal sustainable development and environmental protection (Ahmadi et al., 2013). In geomorphology, water level fluctuations cause the changes in landform and morphology of the coastline, its slope and the type of deposition (Gharib Reza et al., 2012). Coastlines record geomorphological evidence of periodic changes; therefore, it gives beneficial effects in the environmental management of coastal area (Yemani et al., 2019).

In the last few decades, a significant part of the world's coasts has been affected by continuous erosion and retreat of the coastline (Bird, 1985). Climate change and sea level rise have a significant impact on aggravating of changing coastlines (IPCC[1], 2007). Caspian water level fluctuations due to the importance of habitat, recreation, economy and commerce, coastal areas have always attracted attention and population. The fluctuation range of the water level of the Caspian Sea is very high, so that in a period of 48 years (1929-1977), it shows a decrease of about 3 meters, and in a period of 18 years (1977-1995), it has experienced an increase of about 3 meters (Yamani et al., 2017). It is important to prepare a coastline map and determine changes for safe navigation, resource management, environmental protection, planning and sustainable coastal development especially in Caspian Sea. Today, remote sensing data and satellite images are considered as the most efficient source of information for investigating changes in coastal landforms, tidal levels, changes in coastlines (Simon, 2010). Yamani et al (2013) used different types of remote sensing methods to investigate changes in coastlines, such MLC[2], BEC[3], MDC[4] methods. Different tools are used to study the coastline and quantify its changes. One of the most widely used tools for this purpose is DSAS[5] (Thieler, 2009). This tool is installed as an application on the Arc GIS software and by creating longitudinal and transverse sections perpendicular to the coastlines, calculates the changes of the coastline around the created sections, relative to a certain baseline (Mahmoudi et al., 2014) N.N.salguna et al.(2015) studied the coastal changes of Koramandal using ArcGIS method and DSAS tool. Isha et al. (2020) conducted a study in Port Dickson to find out the changes of the coastline in the region. The result of their studies indicates that the pattern of the coastline changed from 1988 to 2019 in the studied area and a lot of erosion occurred between 2005 and 2010. EvaLouise den Boer et al. (2018) used Digital Shoreline Analysis System (DSAS) techniques to identify and measure erosion and sedimentation in coast of East Java. Yemani et al. (2018) investigate the influence of rapid fluctuations of the Caspian Sea and sedimentary balance in the changes of the coastline in the Tajen River delta. The results indicate that transgression and regression of the coast are exactly in accordance with the changes in the sea level. Servati et al. (2017) researched the effect of rapid water level fluctuations of the Caspian Sea on the coasts of Miankale Island and in this research they used Landsat satellite images of 4, 5, 7 and 8 series sensors, historical topographic maps and numerous field visits The results of the research shows that the eight geomorphological models of McBride et al., six models of lateral movement, forward, backward, in situ narrowing, collapse and rotational instability are found in the this region. Khan Mohammadi et al. (2019) by researching and studying the coastline of the Oman Sea using remote sensing time series data, geographic information system and DSAS indicate that the length of the coastline has increased significantly in this 20-year period. Salehipour Milani and Eskandari (2021) and Salehipour Milani and Mazrouei (2021) in evaluating the changes of coastlines in the coasts of Makran using satellite images and the Digital Shoreline Analysis System (DSAS) concluded that the coastal barriers had the most changes in these areas and sandy beaches are the most stable parts of Makran coasts. Also, MIKE 21 mathematical models are used to investigate the hydrodynamics of beaches and its impact on the coastal zone. Karmi-Khaniki et al. (2004) and Mohammadi et al .(2023) investigated the changes in the physical and chemical characteristics of Urmia Lake water due to the construction of Shahid Kalantari highway. The results of this study showed that after the construction of the highway, the height of the waves in the adjacent area has decreased, so that in the winter and spring seasons, the height of the waves in the vicinity of the highway has decreased by at least 25% and chemical parameters of are different from north to south parts of this lake. Fietcher et al. (2006) investigated sediment transport in a southeastern Florida tidal estuary. The results of the field and laboratory studies indicate that the size of the sediments in the estuary is inversely proportional to the distance from the estuary, so that the coarsest grains are located in the mouth of the estuary, and the size of sediments is finer

[1] Intergovernmental Panel on Climate Change
[2] Maximum Likelihood Classification
[3] Binary Encoding Classification
[4] Minimum Distance Classification
[5] Digital shoreline analysis system

to the mouth of the estuary. David et al. (2003) examined the coastal morphology of Tegmouth Bay, England using the numerical software MIKE21, and compared the results of this work with remote sensing images, and finally drew a flow velocity diagram for the different states of the main wave height were discussed on their impact on the coastal morphology.
Sharbati (2013) conducted a two-dimensional simulation of the sea current of Gorgan Bay in the summer season using the MIKE21 software. The results of the model show that the flow pattern, due to the prevailing wind stress, has water input and output from the only open boundary of the model. Lorestani (2013) investigated the effect of hydrodynamics of the Caspian Sea on the changes of the coast line in the Sefidroud delta by simulating sea waves and currents in MIKE21 software. In this research, he explained the movement and effect of waves caused by wind and sea currents in Kiashahr port. The purpose of this research is to monitor the changes of coastlines in Miankaleh coast and Gorgan River delta due to sea level fluctuations using satellite images. The DSAS and Mike21 applied to evaluate the changes of the coastlines and their effects on wave dynamic.

1.1. Regional Setting

The studied area is located in the Iranian southeast of the Caspian Sea. Spit, sandy beach, lagoon and river delta are dominant landform in this area. Its geographical limit is between 53° 04' 56" to 53° 59' 38" east longitude and 36° 47' 8" to 37° 19' 08" north latitude.

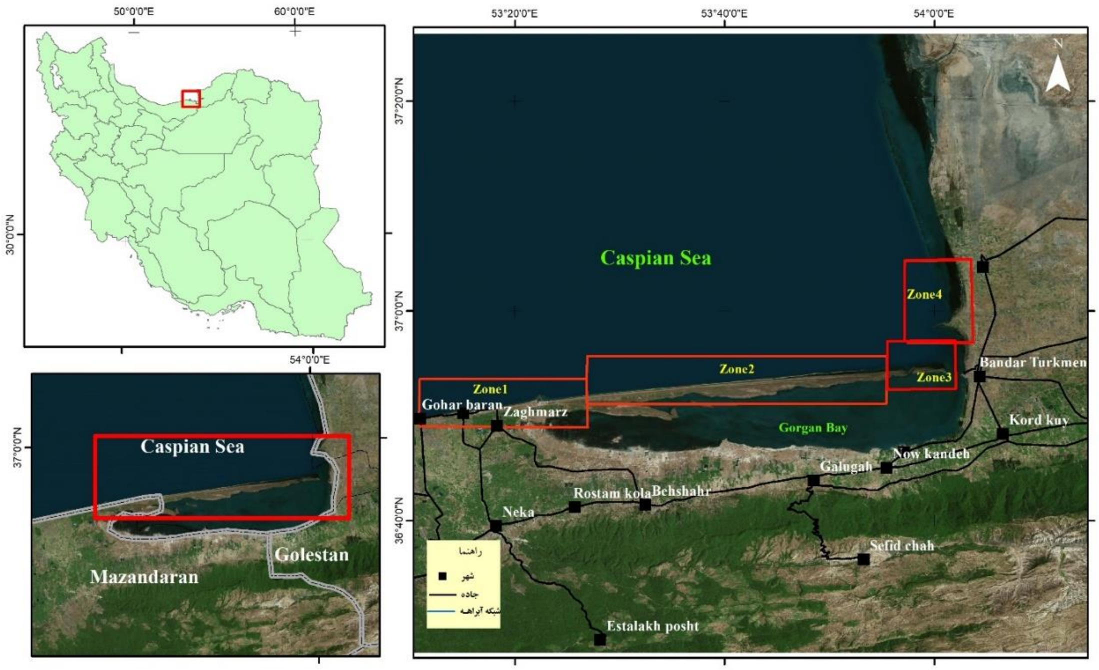

Fig. 1. Geographical location of study area

The most important rivers of the studied area include Qarasu and Gorgan. The Gorgan River entered directly to Gorgan Bay in past time period, but now it has changed its course to the north (Kakroodi et al., 2012). The Gorgan River had a great impact on the morphogenesis of the coastline of this region by transferring the sediment to the sea. The Qarasu River is the only important river that currently enters the Gorgan Bay from the eastern part of the coastal plain. In order to better evaluate the changes of coastlines, the study area was divided into the 4 zone. Zone1 covered area from Gohar Baran to the end of Amirabad port. The second zone includes the Mian Kale spit, and the third zone includes Ashuradeh and Khozeini channel and finally, fourth zone located in the Gorgan River delta and its adjacent areas. At 1978, the water level of the Caspian Sea reached its lowest level (-29) and after that it increased by 2.40 meters until 1998 and reached -27.4 meters. The increasing trend of Caspian Sea water level stopped and the water level dropped and reached -29 by 2023 (Fig. 2).

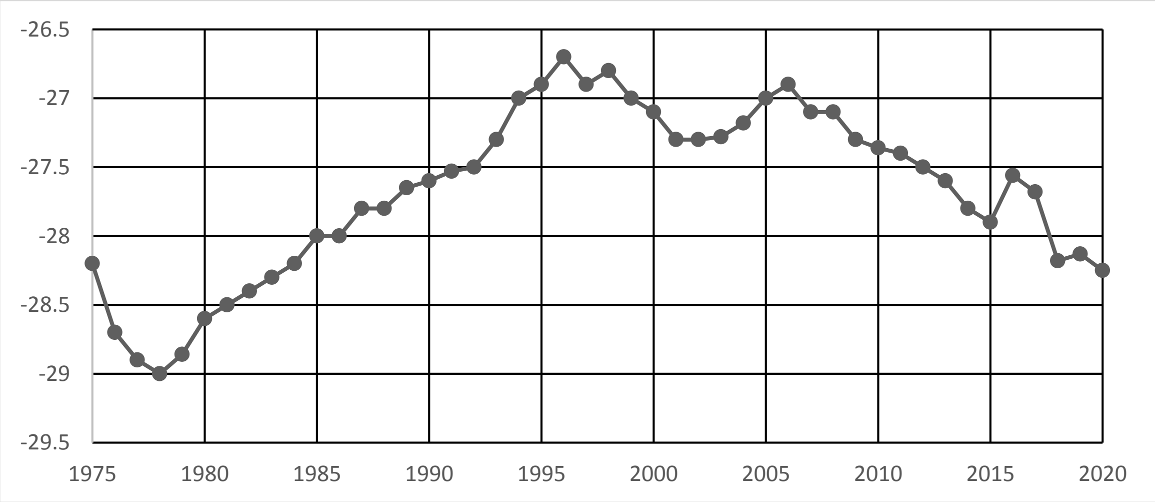

Fig. 2. Fluctuation of the Caspian Sea water level between 1975 and 2020

The annual wind rose of the studied area was determined using meteorological data (wind speed and direction) related to Amirabad station (Fig. 3). The wind direction in the studied area blows from different geographical directions; But the direction of the wind, which has a great effect on the creation of waves and create longshore current and drift, is blowing from the north, northwest. These wind directions are directly related to the currents that are active in the southeast of the Caspian Sea (Mansouri et al., 2012).

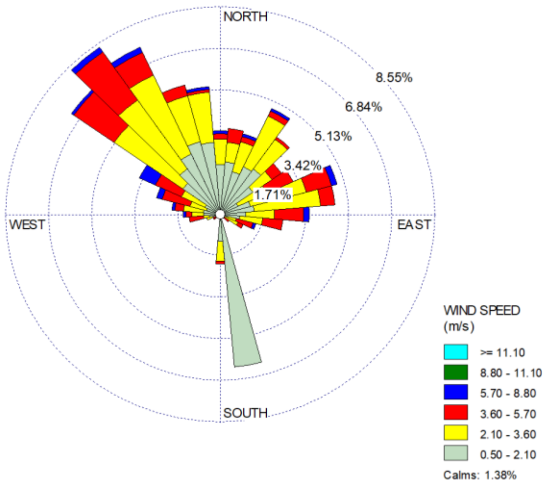

Fig. 3. The annual Wind rose of the studied area according to the data from the Amirabad meteorological station

2. Material and Methods

2.1. Methodology

One of the best ways to extract coastline and its change during the time is the satellite images in different time series. In order to determine the changes of coastlines, Landsat satellite images were used between 1978 and 2023, and these images are related to the years 1975, 1998, 2011 and 2023. After atmospheric and radiometric corrections, NDWI index was used to extract water from coastlines. Besides DSAS system used to quantities measurements of coastline changes. Digital Shoreline Analysis System (DSAS) is a freely available tool that works in Geographical Information System (ArcGIS) software. DSAS calculates rate-of-change statistics for a series of shoreline vector data. Finally, MIKE 21 software has been used to analyze the hydrodynamic processes affecting the morphology of the coast. Hydrographic map with 1:100000 admiralty scale was used to model and mesh the target area in this study. The Amirabad wave and wind data buoy samplings between 2015 and 2018 are considered as model inputs for the implementation of models of waves and currents in Mike 21 (Table 1).

Table 1. Input parameters for the SW model

Description	Parameters
Spectral formulation: Directionally Decoupled Parametric formulation	Basic Equation
Quasi stationary formulation	Time parameters
Newton-Raphson iteration, Maximum number of iteration:500,Relaxation Factor:0.1	Solution technic
Simulated from Flow Model FM: witoutport.dfs0,withouthport.dfsu Withport.dfs0,withport.dfsu	Water level position
Simulated from Flow Model FM:witoutport.dfs0,withouthport.dfsuWithport.dfs0,withport.dfsu	Current Position
Wind generation formula:SPM84	Wind field development model
Gamma data:0.8, Alpha:1	Breaking wave
Nikuradse Roughness,Kn:0.07	Floor friction
Boundary Condition	Boundary situation
Land Boundary	South Boundary (coast)
Lathral Boundary	East boundary
Wave parameters Version1	North Boundary
Lathral Boundary	Northeast Boundary

3. Results and discussion

According to the NSM index in some parts of the studied area, coastline progresses about 4465.28 m and retreats of about 4273 m between 1975 and 2023. These changes have occurred in the eastern part of the study area and in the mouth of Gorgan Bay and Gomishan Lagoon. Due to the lower topographic slope of the coastline and also the sea bed in eastern parts of the study area, rise of the sea water has affected many parts of Bandar-e-Turkmen, Gomishan Lagoon and Khaje Nafs Beach. During this time Ashuradeh and Chepoghli village submerged under water and the residents of these villages were forced to migrate to new places. The lowest number of changes is related to the area between Amir Abad port and Ashurade (before the Khozeini channel). According to the LRR index, an average of coastline progression is 176m, and the regression was about 117m between 1975 and 2023 have. In order to better understand the changes of the coastlines in the study area, the rate of changes was evaluated in the studied zone. The results indicate that the maximum progression of the coastline has been about 1043.3 meters and, in some places, it has retreated about 417 meters, between 1975 and 2023 in the Zone 1 which is located from Gohar Baran to the end of Amirabad port. In relation to the changes of coastlines in this region, it should be considered that the rate of coastline progression in the Zone 1 is not directly due to sea level fluctuations, but the coastline developed due to the construction and development of Amir Abad Port wharf and infrastructures, and the retreat in this area is also subject to the deposition of sediments on the western side of the Amirabad wharf and the lack of proper nourishment of the sediment in the eastern part of this wharf (Fig. 7B). In the Zone 2, which includes the middle part of Miankaleh spit, the rate of change is dependent on sea level fluctuations due to the lack of human intervention. According to the NSM index, the maximum progression of the coastline is about 239 meters and the maximum retreat is about 134 meters. The dominant trend of changes in coastlines has been in progress, and according to the LRR index, it has progressed by about 9.5m.yr. between 1975 and 2023. According to the NSM index, the coastline has prograte about 4465 meters in periods of sea water level retreat in Zone 3. Average annual changes according to the LRR index in this area have been observed with a progression of 176m/yr. at the mouth of Gorgan Bay. Finally, in Zone 4, which includes the limit of Bandar-e-Turkmen to Khaje Nafs, according to the NSM index the maximum progression of the coastline observed in the Gomishan lagoon about 2001 meters, and this progression has been simultaneously to the sea level rise. During the retreat of the sea water in this part, the greatest retreat of the coastline has been observed about 2273m in this region. The average rate of change in this area according to the LRR index was around 18.5 m/yr. and observed from green (maximum progression) to red (maximum regression) in fig (Fig. 4 and Table 2, 3).

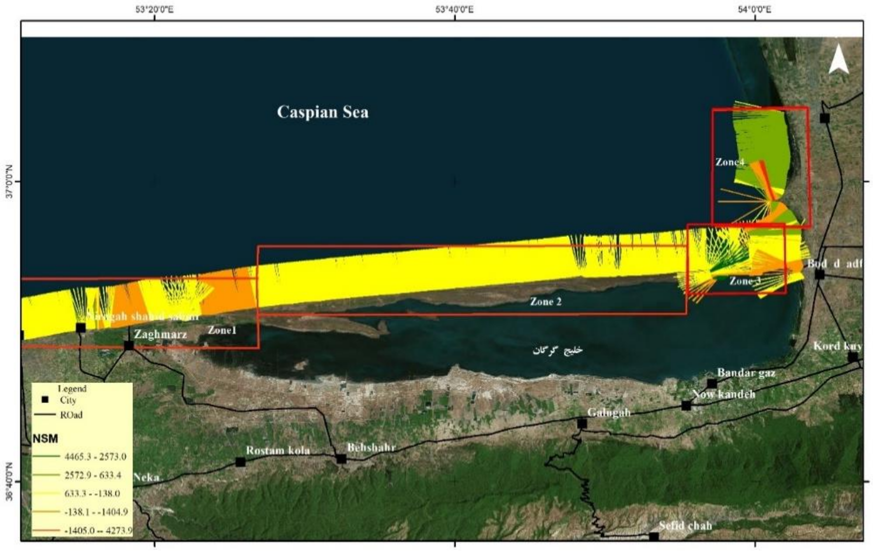

Fig. 4. Coastal change between 1978 and 2023 according to NSM index

Table 2. Coastline changes in the years 1975 to 2023

SCE (m)	NSM (m)	EPR (m/yr.)	LRR (m/yr.)	Range	Zone
	-4465.3	-254-6	-176.3	Max Progression	
4465.3	4273.9	112	117.3	Regression Max	1975-2013
821.6	-184.6	-5.2	-4.6	Mean	

Table 3. Rate of coastal changes in the studied zones between 1975-2023

SCE (m)	NSM (m)	EPR (m/yr.)	LRR (m/yr.)	Range	Zone
52.7	1443.3	23.1	27.1	Max Progression	
1043.3	-417	-9.2	9.7-	Regression Max	Zone1
303.8	-5.1	-0.1	-0.1	Mean	
157.3	238.8	9.5	9.5	Max progression	
1244.8	-131	-3	-3.1	regression Max	Zone2
37.1	5.3	-3	-0.2	Mean	
92.06	4465.3	0.12	176.3	Max progression	
	-4274	-112	-117.3	Regression Max	Zone3
1934.7	596.4	16	15.81	Mean	
9.75	2001.7	72.55	71.93	Max progression	
-	-	-	-	Regression Max	Zone4
2160	684.8	18.6	18.5	Mean	

3.1. Coastal changes between 1975-1998

In evaluating the changes of coastlines in the study area and monitoring these changes, the coastlines of this region are highly affected by this water fluctuation. Between 1978 and 1998, the sea level has raised by 2.30m (Fing. 2). This rate of sea level rise has caused that the coastline recedes by about 4410m according to the NSM index in some parts of the studied area, especially in the mouth of Gorgan Bay. During this period only in Parts of Spit Miankaleh coast progressed about 227m due to the construction of Amirabad piers in Zone1., the coastline regression has been observed at about 2531m in the Zone 2, which shows the great influence of sea level rise on coastal areas. The highest rate of changes in coastline occurred in Zone 3 and in the Ashuradeh area and the mouth of Gorgan Bay, where the coastline has receded by 4410 meters due to the rising sea level. The average regression in the studied area was about 2465 m, which indicate the great impact of sea level fluctuations in this part of the studied area. And finally, between 1978 and 1998, in Zone 4 and in the coastal part of Golestan province from Bandar-e- Turkmen to Gomishan, the predominant trend of coastal was the regression, but the regression rate is lower than Zone 3, and according to the NSM index, it was around 2334m (Fig. 6A and table 5,6).

3.2. Coastal changes between 1998-2011

Between 1998 and 2011, the increasing trend of the Caspian Sea water level has gradually turned into a decreasing and the water level has decreased from -26.3 to -27.4 (Fig. 2). According to the NSM index, the greatest progress in the study area with 2752 meters is observed at the mouth of Gorgan Bay. According to NSM index, between 1998 to 2011 the highest coastal progression was about 432 meters in Zone 1, and only in some parts of the study area due to construction operations, and reduce longshore drift a limited regression was observed in the coastline. In the Zone 2, the trend of coastline progression has increased and reached about 390 meters, and the average progression in this part of the coastline has reached 177 meters. But as in the previous period, the predominant changes are progressing about 4240m, and the average progression in this zone is about 1143m in zone 3. And finally, Zone The highest rate of this progression observed in Gomishan and Khaje Nafas (Fig. 5B, Table 4, 5).

3.3. Coastal changes between 2011-2023

Between 2011 and 2023, the Caspian Sea water level has continued to decrease and has reached -29m, which is almost equivalent to the level of the Caspian Sea water level in 1978. This decreasing trend causes progressed of coastline continues and NSM index reached to 4240 meters, and the average is around 440 meters. The lowest rate of progression is observed in zone 1 with 296 meters according to NSM index, and the progression gradually increased towards the east and reached 390 meters in Zone 2 and 4240 meters at the mouth of Gorgan Bay in zone 3. The coastline progressive process continues and reaches about 2752 meters in the adjacent areas of Gomishan lagoon (Fig. 5C and Table 4, 5).

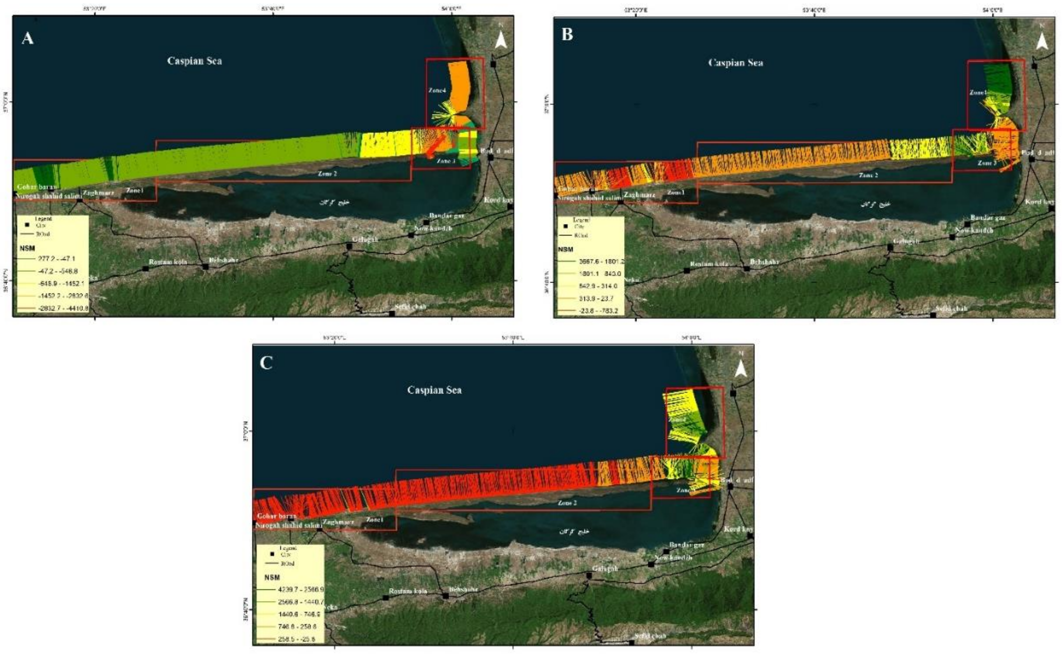

Fig. 5. Rate of coastline change according to NSM index A: 1975-4998, B:1998-2011 and C:2011-2023

Table 4. Coastline changes in the years 1975 to 2023

SCE (m)		NSM (m)		Range	
	0.11	277.2		Max Progression	
	4410.7	-4410.7		Regression Max	1975-1998
695.4		-687.4		Mean	
	-	2751.8		Max Progression	
	2751	167-		Regression Max	1998-2011
349.6		238.8		Mean	
4239.7		4239.7		Max Progression	
0			28.7	Regression Max	2011-2023
449		448		Mean	

Table 5. Rate of coastal changes in the studied zones between 1978-2023

2011-2023		1998-2011		1978-1998			
SCE (m)	NSM (m)	SCE (m)	NSM (m)	SCE (m)	NSM (m)	Range	Zone
-	296.5	423	423	0.11	277.2	Max Progression	
1307.8	-1307.8	-	-167.8	-358.7	-358.7	Regression Max	Zone 1
-109	34.2	-96.3	-38.7	-175.3	-138.8	Mean	

44.4	39.9	-	2531	-	-	Max Progression	
390.9	-	-2531	-	-3859	-3859	Regression Max	Zone 2
-177.4	-177.4	194.6	-194.4	-424.9	-424.9	Mean	
180.9	4239.7	-	3667.6	-	-	Max Progression	
-4239.7	-954.7	-3667.5	-45.5	-441	-441	Regression Max	Zone 3
1272.4	1143.9	-869.7	866.7	-2465.9	-2465.9	Mean	
2752	2752		2975		-	Max Progression	
-	-25.05	-2975	-19.5	-2832.5	2333.8-	Regression Max	Zone 4
988.85	988.4	1005.9	1005.9	-1577.7	-1577.7	Mean	

Fig. 6. A: shoreline Progression in Bandar-e-Turkmen, B: erosion of coastal area due to port construction and decrease longshore drift in Miankaleh, C: water regression beside Bandar Turkmen break wave and D: Bandar Gaz port floor covered by vegetation due to water regression (All picture captured in 2020)

3.3.1. Evaluation of coastline changes and its impact on marine wave dynamics

The DSAS model and changes in coastlines indicate that the increase in the sea level has led to the flooding of many parts of the coastal areas, and the decrease in the water level has also caused the coastal area emerged in the study area. But one of the important issues in evaluating the effect of sea level fluctuations on coastal area is assessing the effects of this fluctuation on marine parameters such as wave and current parameters, especially waves. Because when the water level decreases or increases, the morphodynamic parameters also change and can provide the basis for increasing and decreasing erosion and sedimentation in different areas. Therefore, in this part of the research, the Mike21 model was used to evaluate the effects of sea level changes on wave dynamics. In this model, the hydrodynamic changes were reconstructed in the two years of 1975, as the lowest water level, and 1998 in the high water level of the Caspian Sea.

3.3.2. Modeling hydrodynamics of waves

Mesh of the model

The Mike Zero package and the mesh creation subroutine were used to mesh the main modeling domain in Mike21 software. The boundaries of the modeling area, the coastline, the hydrographic map of the area with a scale of 1:100000, including the Spit of Miankaleh and Gorgan Bay and Gorgan River delta, are included in the modeling domain in 1975 and 1998 (Fig. 7, 8).

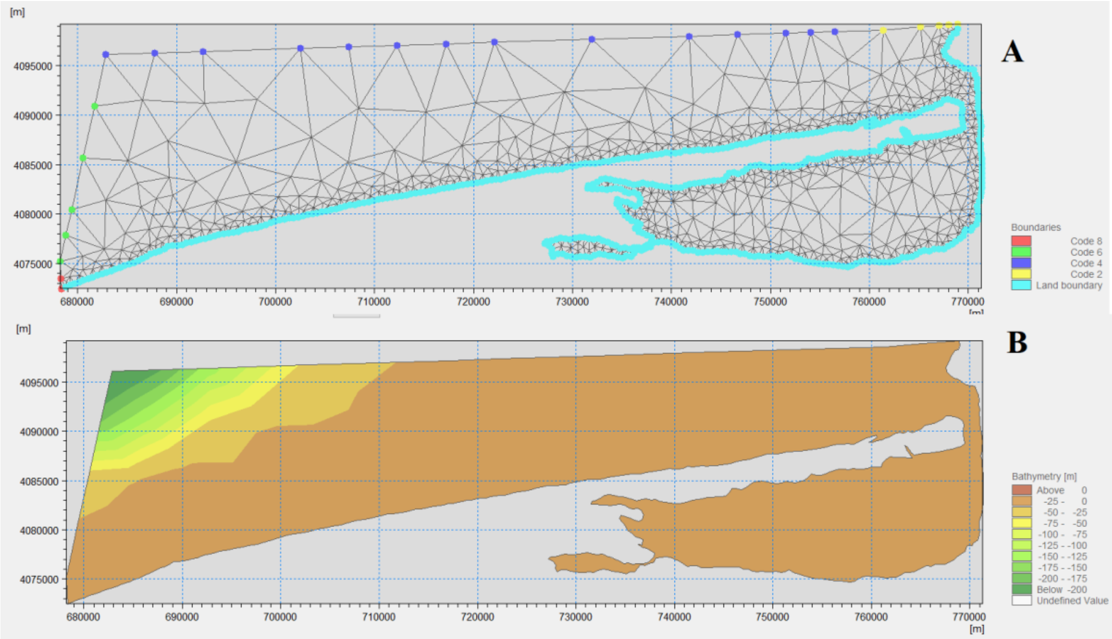

Fig. 7. Meshing and boundaries of the study area and B: depth of the study area in 1975

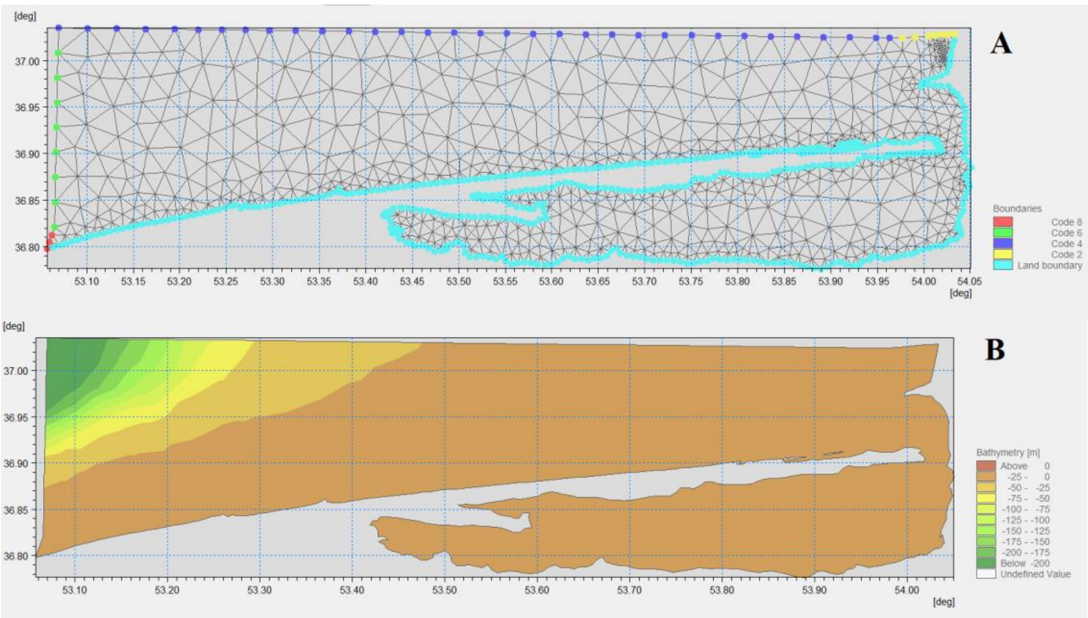

Fig. 8. Meshing and boundaries of the study area and B: depth of the study area in 1998

Waves Modeling

In order to investigate the changes in wave height in the two studied periods (sea level rise, 1998 and sea level fall, 1975), sample points were selected in the two coastal areas of Gorgan River Delta and Spit Miankaleh (Table. 6 and Fig. 9).

Table 6. The location of the sample points in the delta of Gorgan River and Spit Miankaleh

x	Y
54.02713	36.92605
53.95169	36.91604
53.77479	36.89935
53.60657	36.88533
54.02446	37.00883

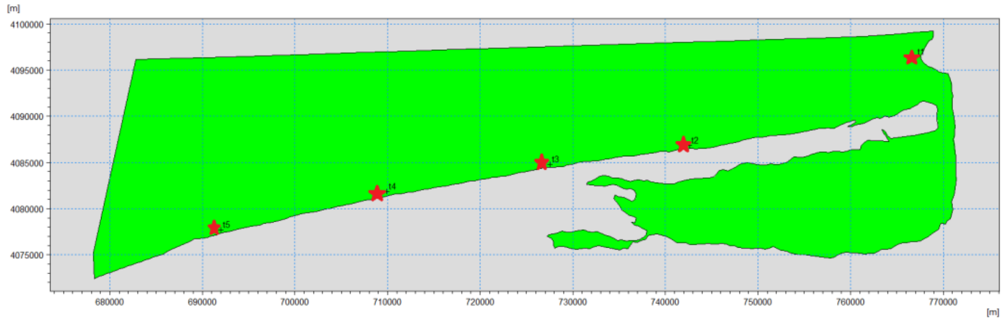

Fig. 9. Wave modeling sample points

The effect of Caspian Sea water level fluctuations on wave height

The highest recorded wave height (1.56 meters) in the studied period is related to the autumn season, therefore the wave data and wave direction in this season were entered into the model as basic data. The dominant wave direction in this area is related to the northeast, and in addition, the highest wave height has also been recorded in these directions.

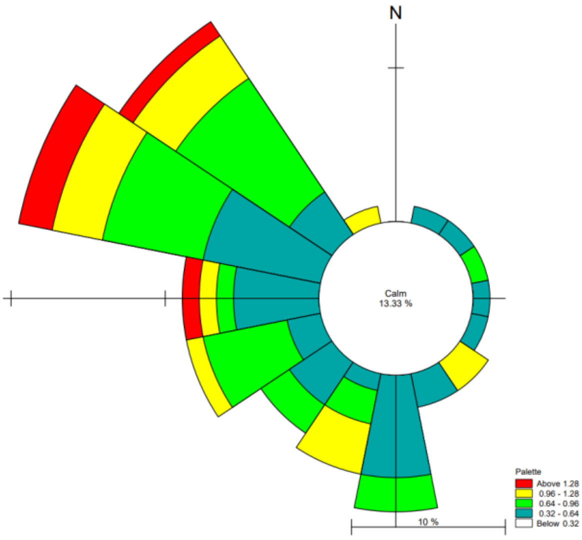

Fig. 10. Wave rose of Amirabad Station in Autumn

3.4. Wave characteristics in coastline (1975)

The wave modeling results indicate that the Maximum dominates wave height in the study area in the fall season according to the coastline of 1975 is related to sample number 5 (0.68 meters) which is located in the west of Spit Miankaleh. and gradually the Maximum dominates wave height decreases to 0.14 meters towards the east and in the Gorgan River delta, because the water depth decreases from the west to the east, especially in the Gorgan River delta (Table 7 and Figure 11). This condition also applies to the maximum wave height, and the wave height at point 5 is 1.31 meters, and this number decreases to 0.23 meters on the east side in the Gorgan River delta. The average maximum wave height in the studied area is about 0.68 meters (Figure 12).

Table 7. Wave height at sample points on the coastline in 1975

Sample Point	1	2	3	4	5	Mean
Average dominates wave height (m)	0.12	0.07	0.17	0.17	0.28	0.16
Maximum dominates wave height (m)	0.14	0.23	0.38	0.4	0.68	0.366
Average maximum dominates wave height (m)	0.25	0.14	0.34	0.34	0.56	0.33
Maximum Wave height (m)	0.23	0.49	0.71	0.78	1.31	0.684

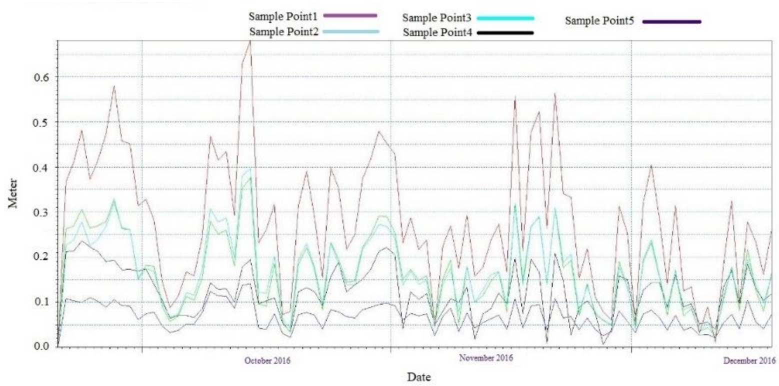

Fig. 11. Maximum dominates wave height (1975)

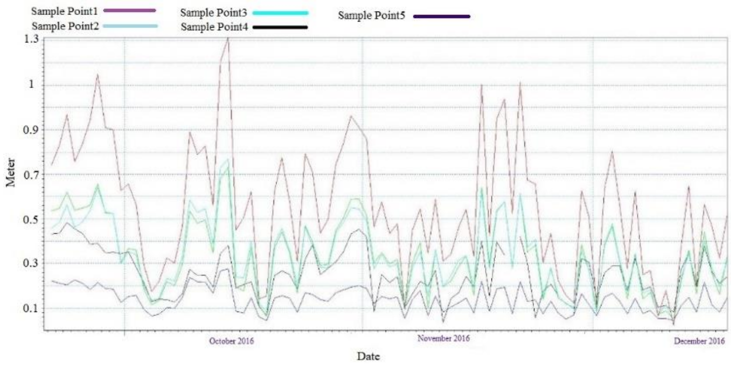

Fig. 12. Maximum height of Wave (1975)

3.5. Wave characteristics in coastline (1998)

The Maximum dominates wave height in 1998 is 0.84m at sample point number 5, which can be attributed to the greater depth of the marine in this part of the coast compared to the eastern part because the Caspian Sea level rise to -27.4, which is possible to provides higher wave height than other parts, and gradually towards the east, and Maximum dominates wave height decreases to 0.45m (Table. 8 and Fig. 13). The average maximum wave height according to the 1998 coastline is 1.12 meters, and in addition, the maximum wave height reaches 1.6m at point 5 and gradually towards the east, the height of the prevailing maximum wave decreases to 0.88m (Fig. 14).

Table 8. Wave height at sample points on the coastline in 1998

Sample Point	1	2	3	4	5	Mean
Average dominates wave height (m)	0.23	0.19	0.21	0.24	0.32	0.24
Maximum dominates wave height (m)	0.45	0.5	0.49	0.64	0.84	0.58
Average maximum dominates wave height m)	0.46	0.39	0.41	0.48	0.63	0.47
Maximum Wave height (m)	0.88	0.98	0.94	1.21	1.6	1.12

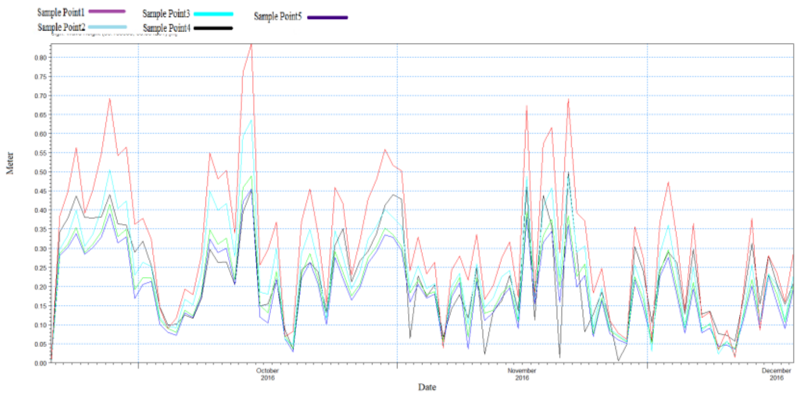

Fig. 13. Maximum dominates wave height (1998)

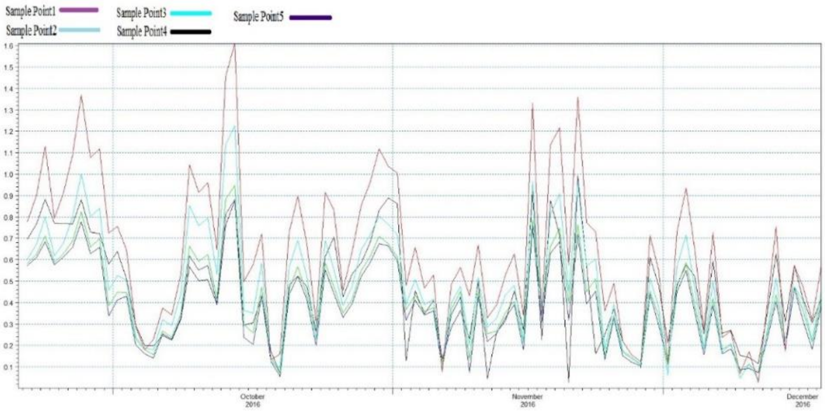

Fig. 14. Maximum height of Wave (m) in 1998

3.6. Wave height changes in 1998 compared to 1975

The Maximum dominates wave height has increased by 21 cm in 1998 compared to 1975, while the highest increase in wave height in the studied area is on the eastern coast and Gorgan River delta with an increase of 31 cm. In addition, the results of the modeling of wave in high and low water table show that the wave height has increased simultaneously with the rise of the sea level, and the maximum wave height has increased from 1.3 meters in 1975 to 1.6 meters in 1998, this increase in wave height besides submergence of coastal areas can intensified the process of erosion in the coastal zone.

Table 9. Changes in the maximum height of the dominant wave between 1975 and 1998

Sample Point	**1**	**2**	**3**	**4**	**5**	**Mean**
Maximum dominates wave height 1998 (m)	0.45	0.5	0.49	0.64	0.84	0.58
Maximum dominates wave height1975 (m)	0.14	0.23	0.38	0.4	0.68	0.366
Range (m)	0.31	0.27	0.11	0.24	0.16	0.21

3.7. Discussion

3.7.1. Forecast future decadal coastline changes

The results indicate that the dominant trend of the Caspian water level fluctuations is regressive and this trend has continued since 1998 up to now. The results also show that the regression and progression of the coastline in different periods of time provide erosion and sedimentation fields in different areas of this coastline. One of the important issues in coastal management is to evaluate the future changes of the coasts, especially in areas where structures such as ports are located near the coast. Therefore, by using the forecasting tool in DSAS software, coastal changes were studied and evaluated for the next 10 and 20-year time periods according to previous coastal in a 4 zone of study area. The results of the 10- and 20-year forecasting changes coastal zone in Zone 1 (Gohar Baran and Amirabad Port) indicate that the dominant trend in the coastline will be the progress of the coastlines. The rate of progression in 2034 compared to 2023 will be around 32m and in addition, this trend will continue until 2044 and the average progression in this part of the coastline will be around 80.3m. But the important problem that can be observed in this part of the coastline is that in the next 10 and 20 years, not only is the rate of progression in coastline is not the same, but the erosion of the coastline is also observed in some parts this area. The results show that a large rate of sediments has been deposited in the west of Shahid Salimi powerhouse due to the disruption of currents parallel to the coast and the reduction of sediment transport by these currents due to reconstruction of break wave in this area (Figure 15 C). This trend was observed during previous periods of time, but in the future this trend will intensify. This process of sedimentation Also will be continued in the west of Amirabad port. In such a way that in 2034 the coastline reached its maximum prorate of about 199m and in the future until 2044 this coastline progress rate will increase to 384m (Figure 15B and Table 10). This volume of sedimentation, which may increase due to the decrease in the water level of the Caspian Sea and also the change in the rate of sediment feeding by the rivers in the region, can have a negative impact on the performance of Amir Abad Port and Shahid Salimi Powerhouse. In addition, due to the reduction of the process of sediment transfer due to the construction of

Shahid Salimi power plant docks and Amirabad port breakwater, due to the lack of allocation of sediment required for the stability of the coastline in recent years in the western part of Amirabad port, the erosion and retreat of the coastline on have given. This process will continue in the future so that the coastline in this part of the coast will recede by 189 meters in 2034 and by 240 meters in 2044.

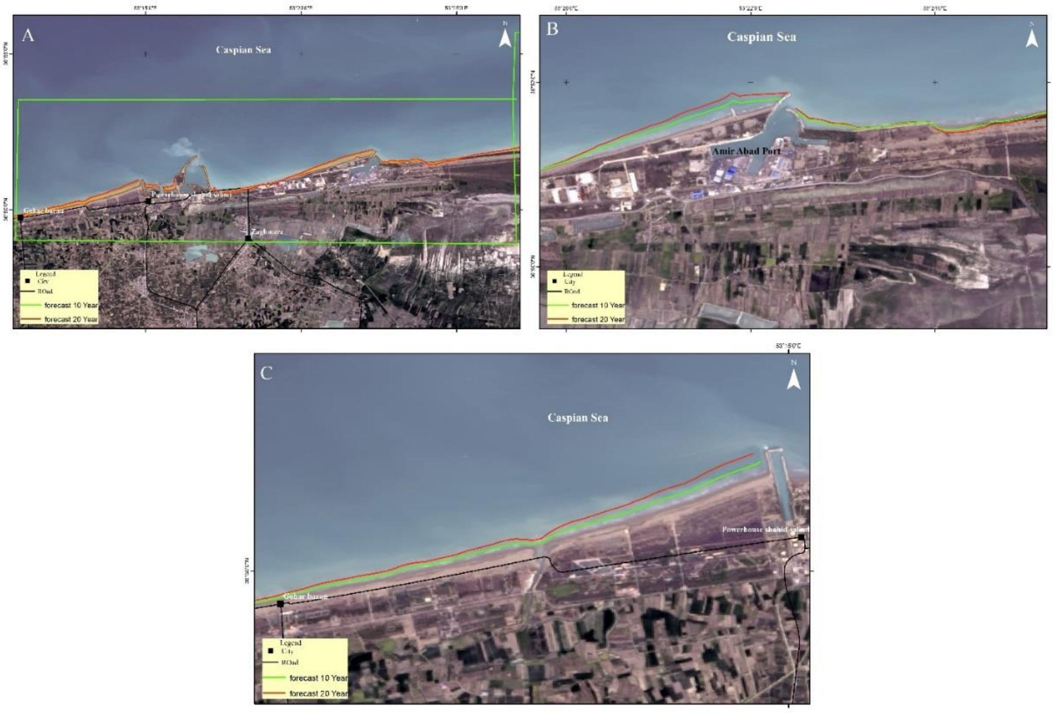

Fig. 15. Coastline changes in 2034 and 2044 in A: Zone 1, B: Amir Ayad Port and C: Shahid Salimi Powerhouse compared to 2023

In zone 2, which is located between Amir Abad port and Khouzini channel in Miankaleh spit, in the period of 10 and 20 years later, the dominant trend will be the progression of the coastline, and this rate will gradually increase towards the east. As mentioned in the previous section, due to the reduction of the slope of the coastal plain and the depth of the sea, the progression trend increases from west to east and this trend will continue in the future. The average progression in 2034 is about 79.5m and in 2044 is 139m. The maximum amount of advance in 2034 is around 564.5m and in 3044 around 1025.4m (Figure 16 and Table 10).

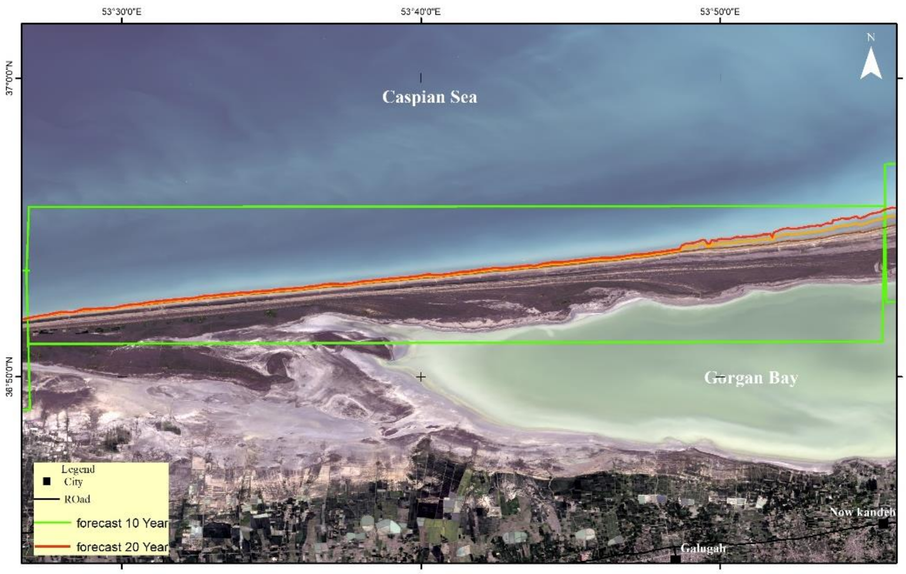

Fig. 16. Changes in coastlines of zone 2 in the next 10 and 20 years compared to 2023

In zone 3 of the studied area that located at the mouth of Gorgan Bay, the trend of progressive of coastline is intensified compared to zones 1 and 2 zone and its average reaches 185m by 2034 and 379m by 2044. The maximum prograte of the coastline shows an increase in the mouth of the Gorgan Bay and the current location of the Caspian Sea water channel to the Gorgan Bay. The continuation of the regressive process of the coastline in the past years at the mouth of the Gorgan Bay will cause the water channel between the Caspian Sea and the Gorgan Bay will be blocked and changed to restricted lagoon.

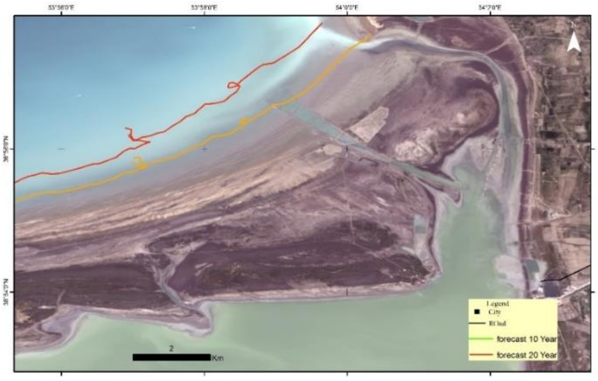

Fig. 17. Changes in coastlines of zone in the next 10 and 20 years compared to 2023

And finally, in region 4, which includes the coastlines of Bandar Turkman, Khaje Nafas and Gomishan, the highest regression rate of coastlines observed in the study area. In this part of the coastline, due to the very low topographic sea slope, if the average advance of the coastline continues in the next 10 years, it will show a regression of about 916 meters compared to 2023 and 1880 meters in 2044, and this in Meanwhile, in the northern part of this region on the Gomishan coastline, the maximum progression will reach 1961 meters in 2034 and 4947.5 meters in 2044 (Figure 18 and Table 10).

Fig. 18. Changes in coastlines of zone 3 in the next 10 and 20 years compared to 2023

Table 10. Forecast coastline changes in 2034 and 2044

2044	2034	Range	Zone
384.66	199.72	Max Progression	
-239.82	-189.43	Regression Max	Zone1
80.26	32.27	Mean	
1025.4	564.57	Max progression	
-	-	Regression Max	Zone2
139.3	79.55	Mean	
1025.4	648	Max progression	
-	-	Regression Max	Zone3
279.55	185	Mean	
4947.46	1961.44	Max progression	
	-	Regression Max	Zone4
1879.97	-915.8	Mean	

As mentioned in the issue of waves, an increase in sea level causes an increase in wave height and will intensify coastal erosion and a decrease in it leads to a decrease in wave height, and as a result, a decrease erosion and an increase in sedimentation on the coastline plain. Due to the continued decrease in the water level of the Caspian Sea and the consequent increase in the rate of sedimentation, it seems that the progression of the coastline under the influence of the decrease in the power of wave erosion will intensify in the future, and many coastal facilities in the study area will be out of operation or they will need reinvestment in the future for development.

4. Conclusion

Coasts are very dynamic areas that are influenced by the processes related to water level fluctuation. On the other hand, the processes governing land environments directly and indirectly influence the formation and evolution of those factors. The climatic conditions governing the coastal areas also have a determining role on the morphological characteristics of the coasts in relation to the formation processes and living conditions. The presence of man in the coastal environment and his exploitations causes changes in coastal landscapes. Monitoring the trend governing water level fluctuations and changes in the coastlines is one of the most important parameters needed for the management of coastal areas. The results of this research indicate that the fluctuations of the Caspian Sea between the 1978 and 2023 had a great impact on the coastlines of the study area, and this effect intensified in the eastern region of the study area, especially the mouth of Gorgan Bay in Ashuradeh region. The results of wave height modeling by Mike21 software indicate that, with the increase in water level in 1998 compared to 1975, the dominant wave height and the maximum wave have increased significantly. Caspian Sea level rise, not only submerge coastline but also the wave height had also increased and this has led to the intensification of the erosion of the coastline. The results indicate that sea level rise can provide the basis for the increase of erosion in these areas, the decrease of the sea level as in 2023 can also lead to the reduction of the erosion processes and sedimentation increase in coastal area, especially in the mouth of Gorgan River and the eastern part of Miankaleh Spit. Therefore, land planners to the development of the sea base, such as the development of ports, should measure the effects of the decrease and increase in the water level of the Caspian Sea in the long terms.

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