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Grain-size characteristics of seafloor sediment and transport pattern in the Caspian Sea (Nowshahr and Babolsar coasts)

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ABSTRACT

The aim of the current study is to determine the equilibrium beach profiles of the coasts of Babolsar and Nowshahr in the southern Caspian Sea. Using depth field data collected from two beaches in the period from 2018 to 2019, seasonal beach profiles and equilibrium beach profiles of the study area were extracted. To investigate the type and transfer of bed sediments, samples were collected from depths of 0.5, 1.5, 3 and 5 meters and were transferred to the laboratory for granulation. The results show the predominant type of sediments in Babolsar and Nowshahr are fine sand with an average of 82.39% and 82.12%, respectively. Also, the percentage of fine-grained sediments, including very fine sand and silt have increased from nearshore to offshore. In the west-east, the median diameter of sediment and the profile slope decreased, from there, the erosion and deposition rate in the two regions has changed. In the western regions, the diameter of beach sediments is more than in the eastern regions due to strong sea currents and relatively coarse-grained sediments from the rivers of western Mazandaran, as well as human activities.

1. Introduction

One of the important attempts in coastal engineering and construction of coastal and offshore structures is to understand the concept of how sediments are transported and the analysis of erosion and deposition in different regions. The shape of the beach profile is the result of natural forces that affect the structure of beach sediments. The beach profile is one of the most important parameters for beach analysis. Beach profiles are constantly changing in different parts of the world, due to factors such as waves, sea currents and water level conditions that cause the transfer and displacement of sediments [1]. These changes mainly occur in the vicinity of the beach region where the effects of breaking waves are more evident. It can be mentioned that after the breaking waves process, a lot of energy is transferred to the seabed by waves and sea currents, which cause the sediments to move and eventually lead to the deformation of the beach profile [2]. In most places, the erosion of mountains and the transfer of erosive products to the shoreline are transported to the sea by rivers, and after transfer, they are eroded and substituted by waves and sea currents. In fact, the shape and size of sedimentary grains also affect their movement and transport in the marine environment, so that a flat grain certainly behaves differently than a spherical grain in aqueous media [1]. Sediment particles are transported in two main modes: bed load and suspended load. The bed load is a part of the total load that is moving in the form of rolling and jumping in constant contact with the seabed. So, it can be concluded that accurate prediction of sediment transport rate is an important element in morphological studies of riverine, coastal and marine environments [3]. For marine environments, the sediment transport process becomes more complex due to the presence of oscillating currents, the interaction between constant and oscillating currents, as well as the effect of tides and wind-induced waves [4,5]. In addition to the factors mentioned about beach profile changes, water level is also an important factor in the process of natural activities of water basins. If there are changes in the mean sea level, then there are also changes in the beach profile. Evaluation criteria beach profile changes is the beach equilibrium profile, which is considered as an indicator. The equilibrium profile shows the final trend of the beach profiles. In fact, in order to study the changes or relative stability of beach profiles during different periods, it is very important to study the equilibrium (average) profile [6,7]. Equilibrium profiles are also widely used to predict beach profiles in marine structures and projects [8,9]. Indeed, the equilibrium profile is the result of a balance between the constructive and destructive forces. Constructive forces appear after the storm, and move the sand the onshore. Finally, the beach profile reaches equilibrium over an average of a long period of time and in nature, it is considered as a dynamic concept, because the characteristics of waves (height, direction and period) and water levels are continuously changing and evolving [1]. The equilibrium profile is used as a model for analyzing beach profile changes over different periods of time [10,11,12]. During the study of changes in sedimentary environments, the changes in nearshore portions are greater than offshore portions. Sediments located offshore are often softer than nearshore sediments [1]. In a study conducted in 2007 in the marine regions of Noor, during sampling conducted every two months through the year, the type and percentage of bed sediments were examined. According to the obtained results, the highest amount of bed sediments was very fine sand with an average of 90.594% [13]. Also, the process of modeling sand transfer using Mike 21 in Gorgan Bay shows that nearshore sediments have changed significantly compared to offshore portion [14]. During field measurements, the results of sediment sampling from the nearshore of Miankaleh, Sorkhrood, Nattered, Anzali, Talesh and Astara, show that finer sediments appear at greater depths [15]. Due to the fact that fine-grained sediments are directed to deep zone due to sea currents, but sometimes due to the adhesion of sediments such as silt and clay, according to the Hjulstrom diagram, more force is needed to carry them by sea currents [16]. This event in some beaches reduces the percentage of fine-grained sediments at great depths. In another study in the Caspian Sea, beach profiles on some coasts of Mazandaran and Gilan, according to available measurement data (some seasons) related to 2013 have been studied. The seasonal beach profile has been compared to the equilibrium profile of some mathematical models [17]. With careful redundant and continuous studies, we can find the type of performance of these beaches in different seasons and years, and then suggest useful solutions for the proper use of these regions. In the present study, according to the investigations, the beaches of Babolsar and Nowshahr are among the tourist cities of Mazandaran province, which are located in the east and west of Mazandaran, respectively (Figure 1). They are also very prominent in terms of business activities Nowshahr and Babolsar have a high commercial position due to the construction of the port. Therefore, the study of changes in the seabed and coastlines in these regions is of particular importance, because with detailed studies and continuous analysis, it is possible to know the type of performance of these beaches in different seasons. Following that, more useful strategies for the proper exploitation of these regions can be presented and also, equilibrium beach profile is the principal concept assumed by most numerical modeling. Thus, in order to apply coastal engineering projects, the predicted profile of equilibrium should be close enough to the measured profile.

2. Materials and methods

2.1 Study area

In this study, transverse profiles of the beaches of Babolsar (36° 42' 55" *N*, 52° 40' 38" *E*) and Nowshahr (36° 39' 42" *N*, 51° 29' 40" E) in Mazandaran province located on the southern Caspian Sea coast were studied. The Caspian Sea is the largest inland water basin located in the Eurasian region. The lake is surrounded by the Caucasus Mountains in the west, the Alborz in the south, and the vast desert in the north and east [18,19]. The surface of the lake has changed frequently throughout history. In fact, geological and climatic processes are effective parameters in changing the water level of the Caspian Sea [20]. Hence, the change in river water inflow is one of the most important parameters affecting the water level fluctuations of this sea [21,22]. Beach profiles along the Mazandaran coast (Figure 1) were measured Four times per year in mild conditions during autumn, winter, spring and summer seasons so that seasonal variations could also be considered.

Figure 1. Study area on the southern coast of the Caspian Sea in Mazandaran province

2.2 The field measurement scenario

For the purpose of the present study, in order to determine the equilibrium profile in the two beaches, measurements were done in both land and sea in a cross section which was in the last month of autumn (2018), winter, spring and summer (2019), and once in each season. Initially, in the land part of the coast, the Theodolite mapping camera was utilized to capture data such as distances and heights of different points relative to a base surface (Figure 2a). The coordinates of the desired stations were extracted from Google earth and recorded in GPS[1] (Figure 2b).The beach profiles were surveyed with a theodolite, leveling instruments, and graded stave in combination with a marine compass [23]. The beach profiles extend to a depth of 8 meters, which is approximately 1000 meters from the shoreline. As suggested by Emery (1961), a water depth gauge board was used in the initial part of the beach profiles, while a depth sounder (Figure 2c) was used in deeper waters (up to 8 m). The measurements were referenced to a fixed criterion on land (benchmark).

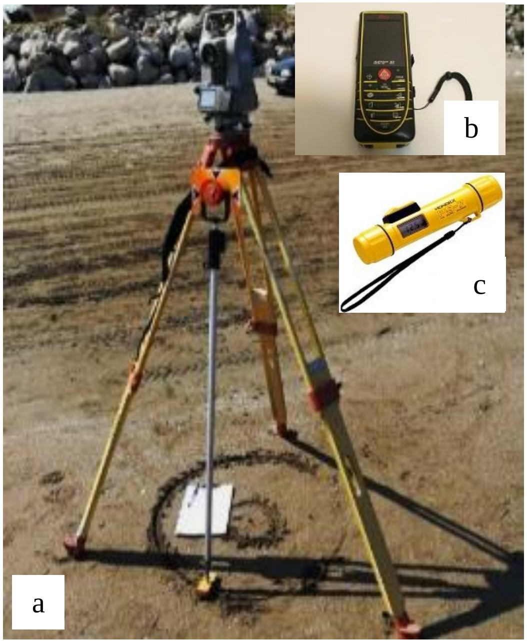

Figure 2. Theodolite mapping camera (a), GPS (b) and depth sounder (c)

The base level was considered consta nt during the measurement period in both beaches. In the sea, 19 stations in Babolsar and 17 stations in Nowshahr were considered to measure water depth (Figure 3a, b). The first and second stations were regarded at the distances of 10 and 30 meters from the shoreline, respectively. The distance between two consecutive stations in this region was 30 meters from a distance of 30 to 300 meters to the sea, and the distance between two consecutive stations was 100 meters from 300 meters to deep zone (closure depth). Based on the obtained depth measurement data, seasonal transverse profiles and mean (equilibrium) profile of Babolsar and Nowshahr beaches were plotted. In the present study, due to the seasonality of the measurements, the average seasonal data of significant wave height related to each of the cross sections of the study area was used. Therefore, in order to calculate the closure depth according to Equation (1), the significant wave height data were received from the Ports and Maritime Organization related to Babolsar and Nowshahr regions during four seasons, (www. Pmo.ir).

$$h_c = 6.75\overline{H}_s \quad (1)$$

Where $\overline{H}_s$ is the annual average of significant wave height in meters [24].

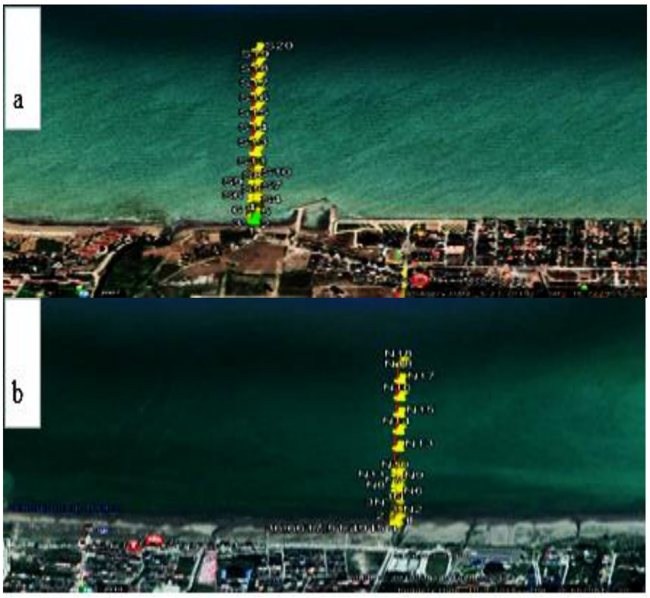

Figure 3. Beach profiles a) Babolsar, b) Nowshahr

At the same time, to investigate the type and percentage of bed sediments as well as to estimate the average diameter of the sediment, bed sediment samples were taken by Van Veen Grab at depths of about 0.5, 1.5, 3, and 5. They were transferred to the laboratory for granulation (Figure 4a, b, c, d).

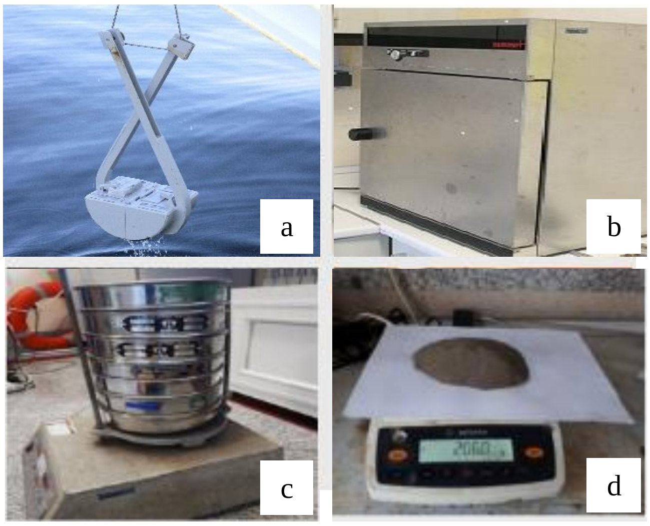

Figure 4. Instruments for measuring sediments a) Van Veen Grab, b) Oven, c) Shaker and d) Laboratory Scale

First, the sediment samples were washed with oxygenated water to separate from the excess material, and then the samples were dried in an oven at 105 ° C for 24 hours. Then, Shaker was used to investigate the granulation. In this regard, sieves with mesh numbers of 30, 60, 100, 200 and 500 with diameters of 600,

[1] Global Positioning System

250, 150, 75 and 25 micrometers, respectively, were used. Sediment samples were sieved for 15 minutes by Shaker. Finally, the residual weight of sediments on each sieve was measured. Gradistat statistical software was used to calculate the type and percentage of bed sediments and also to estimate the median diameter of the sediments [25]. For this purpose, the diameter of the holes of each sieve, and the weight remaining on each sieve (in terms of grams), were given to the software as input data.

3. Results

3.1. Granulation of bed sediments

Using the output data of Gradistat statistical software, the average percentage of bed sediments during the four seasons at the desired depths were calculated (Figure 5). According to the sediment percentages in Babolsar and Nowshahr regions, from the nearshore to the deep zone, in most cases, coarse and medium sand nearshore had a higher percentage than the deep zone. In fact, with increasing depth, the percentage of fine-grained sediments, including very fine sand and clay increased, while coarse and medium sands had a decreasing trend. Because waves and sea currents play a key role in sediment transport, the motion of a particle of sand is affected by the forces acting on it. If the forces are not strong enough to push the particles out of position, then the particle will not move. In fact, ocean currents have the ability to carry sediments that are smaller in diameter than other sediment grains. Thus, smaller diameter sediments are transported away from the coast and only larger diameter sediments remain nearshore [1]. As a result, sediments in the offshore portion are often softer than nearshore sediments. According to the calculations of the type and percentage of sediments, the average percentage of sediments in autumn, winter, spring and summer is calculated in Table 1. In both east and west stations, the predominant type of bed sediments is fine sand, and the lowest percentage of bed sediments is allocated to the silt. According to obtained data related to the significant wave height (www. pmo.ir), the closure depth was calculated in Babolsar and Nowshahr (Table 2). Then, in order to investigate the changes in beach profiles in the desired stations, according to the measured data and closure depths, the mean (equilibrium) profile was extracted from different seasons.

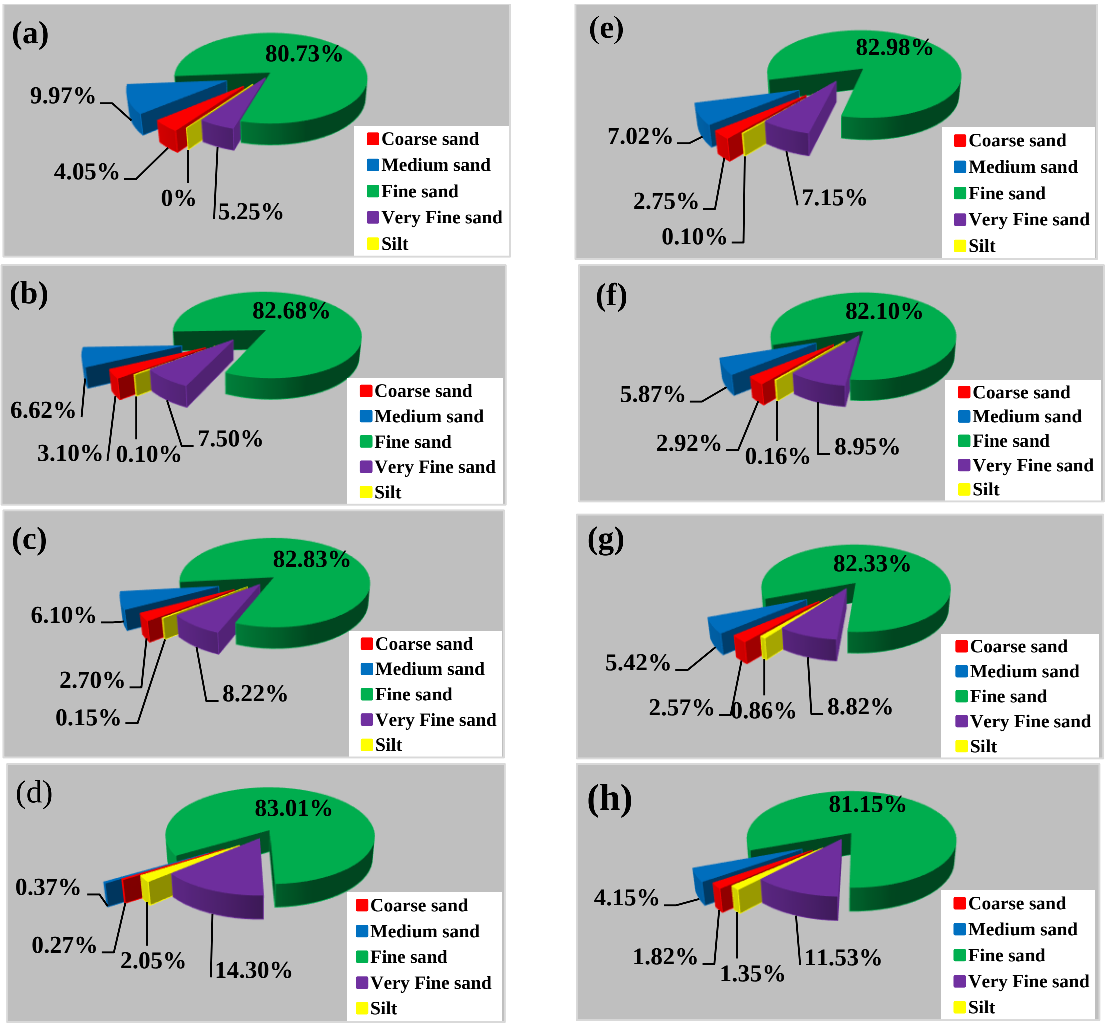

Figure 5. Comparison of the average percentage of bed sediments at depths (a: 0.5 m) (b: 1.5 m) (c: 3 m) (d: 5 m) in Babolsar and depths (e: 0.5 m) (f: 1.5) (g: 3 m) (h: 5 m) in Nowshahr.

Table 1. Average percentage of sediments in autumn, winter, spring and summer

		Average				
		Coarse sand (%)	**Medium sand** (%)	**Fine sand** (%)	**Very Fine sand** (%)	**Silt** (%)
Babolsar	Autumn	1.8	4.3	82.7	11	0.36
	Winter	2.97	3.7	83.75	9.9	1.6
	Spring	2.25	3.67	88.85	4.85	1.5
	Summer	4.1	11.4	74.27	9.35	1.7
Nowshahr	Autumn	2.55	4.75	75.47	16.22	1
	Winter	2.2	4.97	88.82	3.67	1.2
	Spring	1.65	3.05	92.75	2.15	0.5
	Summer	3.67	9.67	71.45	14.42	0.5

Table 2. Closure depth related to the beaches of Nowshahr and Babolsar in four seasons

	Nowshahr				**Babolsar**			
	Autumn	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**
$\bar{H}_s\ (m)$	0.791	0.760	0.741	0.707	0.859	0.771	0.681	0.743
$h_c\ (m)$	5.33	5.13	5	4.77	5.79	5.20	4.59	5.01

3.2. Babolsar beach profiles

Based on the field data, according to Figure 6, the desired profiles were drawn during the four seasons. In nearshore, from the shoreline to a distance of about 450 meters, several bars and berms are observed at different depths that have been changed during different seasons. In fact, most of the seabed changes in each season, compared to other seasons, occur in nearshore due to the direct effect of waves on the seabed. In fact, in these regions, due to the decrease in depth and the subsequent process of breaking waves and the impact of their energy on the seabed, beach sediments are eroded and transported by waves and sea currents in different directions. As a result, erosion and deposition occur more intensively nearshore, which is one of the reasons that has causes of the deformation of the seabed in different seasons. According to studies conducted to compare the two profiles of autumn and winter, the winter profile is eroded from a distance of 100 to 250 meters from the shoreline compared to the autumn due to the number of stormy days in winter. Hence the eroded sediments settled in the distance of 300 to 400 meters, and the depth has decreased compared to autumn. Because in winter, the bars and berms were eroded at a distance of 100 to 250 meters due to the process of breaking waves and turbulence, and sediments were transported to the sea (deeper zone), these sediments eventually interfered with the sediments transported to the beach and caused the formation of a wide berm with a length of 100 meters at a depth of 3.5 meters in winter. In winter, the energy owing to breaking waves increased due to more stormy days and as a result, the eroded sediments were transferred to the sea by return currents. In the surf zone, they collided with sediments that had transferred from the sea to the shore and formed bars. In the spring, the beach profile was eroded at a distance of 100 to 200 meters and also at a distance of 350 meters to deep zone, and then the eroded sediments were transported to the sea. As a result, the depth changes had an increasing trend compared to winter. In summer, due to the low height of the waves compared to spring, sediments were gradually transferred from offshore portion to nearshore, so that they settled at distances of 10 to 50 meters as well as 90 to 250 meters, and during the deposition process, depth changes have been decreasing compared to spring. In summer, due to the prevailing waves with small wave heights, sediments were gradually transferred from the offshore portion to the nearshore, and bars and berms were formed in these regions because of the energy reduction due to breaking waves. So, from a distance of 450 meters to the coast, due to the reduction of the impact of the waves on the seabed and the consequent reduction of sediment transport rate, slight changes have occurred in the beach profile. In order to investigate the variation in the profiles of different seasons compared to the mean (equilibrium) profile (Figure 6), the beach profile has a berm and bar, in autumn, at distances of 100 to 200 meters from the shoreline compared to the mean profile. In winter, the depth has decreased at a distance of 300 to 400 meters due to erosion and sediment transfer away from the beach, in spring, the beach profile was eroded at a distance of 100 to 210 meters from the mean profile. Finally, in summer, the erosion process has occurred based on the mean profile at a distance of 250 to 600 meters from the shoreline. These sediments are gradually transferred by waves to nearshore, so that the bars have been created due to the deposition of sediments transferred to these regions at the distances of 100 and 190 meters. So, most seabed changes have occurred nearshore, while in deeper zone, seasonal beach profiles have changed slightly compared to the mean profile due to reduced sediment transport. The mean profile has also a berm at a distance of 30 to 60 meters at a depth of 0.5 meters and the profile slope equal to 0.018 at a distance of 60 to 150 meters and a bar at a distance of 200 meters.

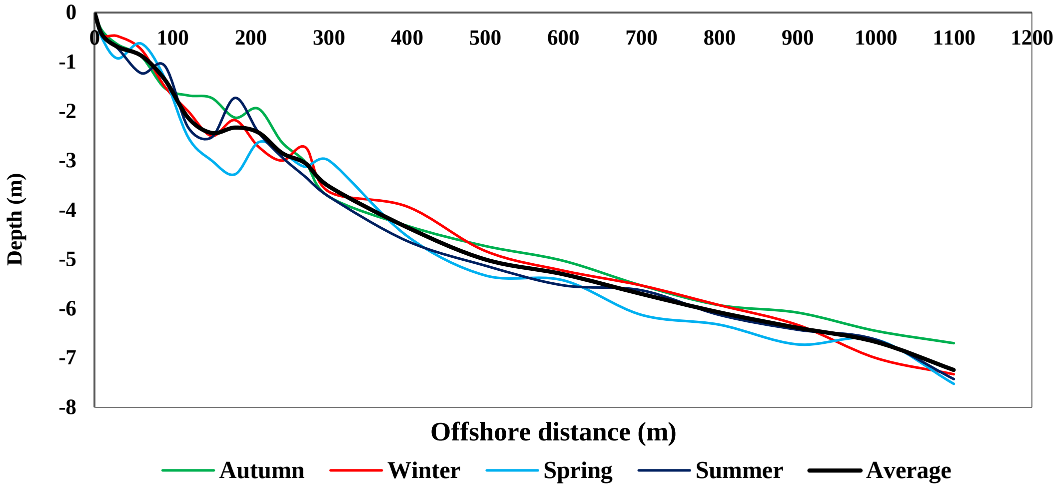

Figure 6. Babolsar beach profiles measured in four seasons (2018-2019)

3-3 Nowshahr beach profile

Based on the depth measurements performed during the study period (Figure 7), a 100-meter-wide berm was observed at a distance of 400 to 500 meters from the shoreline. Most of the seabed changes occurred in the form of bars and berm movement at a distance of 100 to 550 meters from the shoreline in the depth range of 1 to 5 meters, due to the effect of waves on the seabed in this region. In considering the changes of the bed in different seasons, in winter, the process of breaking the wave has occurred more intensively nearshore and sediments have transferred to the beach due to stormy conditions and increasing wave height. The depth increased due to the erosion of sediments compared to autumn at a distance of 180 to 250 and 390 to 510 meters. Finally, these eroded sediments settled at distances away from the beach. In spring, compared to winter, the depth has increased from the shoreline to a distance of 250 meters owing to erosion and transfer of sediments to the beach. In summer, the sediments gradually transferred from the deep zone to nearshore due to the decrease in the average significant wave height compared to spring, so that they settled from the shoreline to a distance of 170 m, and the depth changes have had decreasing trend compared to the spring. Also, a bar has been formed at a distance of 250 meters due to deposition. The profiles almost overlap from a distance of about 550 m to the deep zone during the four seasons, which indicates a reduction in the impact of the waves on the seabed and from there, a reduction in the erosion and deposition process. Then, the seabed changes were examined in relation to the mean profile, which was the result of transfer and displacement of sediments during different seasons. In autumn, the depth has decreased compared to the mean profile up to 120 meters from the shore, and also due to the bar created at a distance of 200 meters. In winter, the beach profile is eroded from a distance of 50 to 120 meters from the shoreline, compared to the mean profile, and the eroded sediments are moved to a deeper zone. However, in summer, the depth has decreased at a distance of 150 meters from the shoreline compared to the mean profile, due to the sediment transfer to nearshore. The mean profile from the shoreline to a distance of 150 meters has the profile slope of 0.014 and a berm at a distance of 190 to 210 meters from the shoreline. The mean profile slope at a distance of 290 to 400 meters is equal to 0.011. There is also a berm 150 meters long at a distance of 400 to 550 meters from the shoreline. Changes in sea level in different seasons has been another factor in changes in seabed. Measurements recorded by Theodolite mapping camera, used record shoreline changes, show shoreline movement is affected by changes in sea level. According to the results obtained in Babolsar and Nowshahr in autumn, due to the decrease in river inflows, a period of decreasing sea level was observed. In winter it remains at the same level with slight changes. Subsequently, because of the increase in the inflow of rivers including the Volga into the Caspian Sea, the increase in sea level began in early spring and has decreased in late summer. Therefore, it can be said that in addition to sea waves and currents, changes in water level have also played an important role in the movement of sediments and consequently changes in the seabed. By calculating the profile slope during the four seasons in the studied area (Figure 8), the profile slope of Babolsar (eastern areas) is less than Nowshahr (western areas). This was related to factors such as grain size and the intensity of the sea currents. As can be observed in Table 2, the median diameter of the bed sediment particles decreased from west to east, which was due to the increase in the percentage of fine-grained sediments in the eastern regions compared to the western regions.

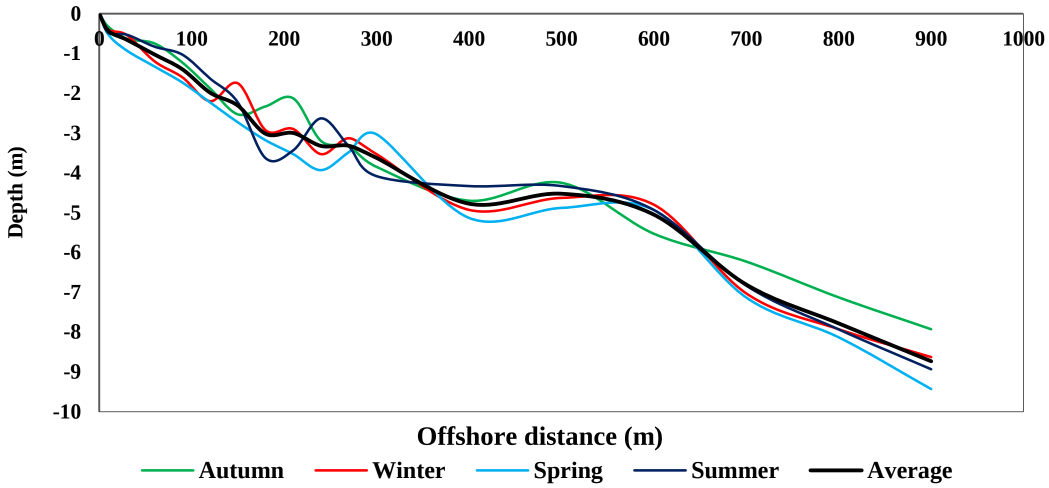

Figure 7. Nowshahr beach profiles measured in four seasons (2018-2019)

In fact, due to the weakening of sea currents in the west to east direction, finer sediments are transported by sea currents, so that their percentage has increased in the eastern regions. As a result, due to the existence of weak sea currents and fine-grained sediments, the possibility of deposition has increased in Babolsar more than Nowshahr, following which the profile slope has decreased.

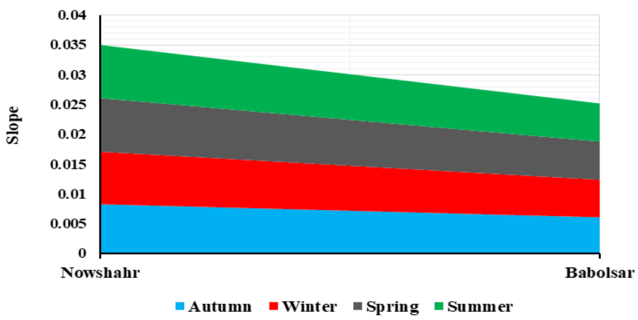

Figure 8. Bed slope changes of Babolsar and Nowshahr beaches in four seasons

4. Conclusion

Changes in beach profile shape occur as a result of changing wave conditions, which can be due to a single storm of unusual magnitude, or seasonal changes in repeated storm intensity. According to the results, the maximum change in the beach profile during different seasons have occurred in nearshore. So that the most changes in the seabed in Babolsar and Nowshahr have been observed at distances of about 450 and 550 meters from the coastline, respectively. In nearshore, following the process of breaking the waves due to the decrease in depth, the energy caused by breaking waves was transferred to the body of water, which eventually caused turbulence in these regions. Also, the process of erosion and deposition more intensely occurred during the seasons in the nearshore than in the offshore portion. In fact, most of the sediment movement and transfer takes place up to the closure depth, and the seabed, due to the minimal impact of the waves on the seabed, has not changed much from this depth to the offshore. The bed profiles of Babolsar and Nowshahr were compared with the results of other studies, including a study conducted by Ataei et al. (2014) in the Caspian Sea. Due to the topography and slope of the seabed, the beach profile had a good compatibility in the eastern regions with the Babolsar profile in the present study. Several bars and berms had been seen at a distance of about 450 meters from the shoreline, and in the depth between 0.5 to 5 meters. In fact, most of the seabed changes occurred up to a distance of about 450 meters from the shoreline, and Babolsar seabed had not changed much over years from this distance to the deep zone. But the Nowshahr beach profile was different in comparison to the Tonekabon seabed in the western regions, due to its wide berm in the bed. By studying the type and percentage of bed sediments in Babolsar and Nowshahr, fine sand has the highest amount with an average of 82.39% and 82.12%, respectively. According to the studies conducted in the two study areas, from nearshore to far offshore, the percentage of fine sediments has increased. In Babolsar (Nowshahr), at a depth of 0.5 meters, very fine sand was 5.25% (7.15%) and silt to 0% (0.10%), and with increasing depth to 5 meters, the very fine sand and silt are 14.30% (11.53%) and 2.5% (1.35%), respectively. In fact, sea currents returning to the sea are capable of carrying fine-grained sediments. Therefore, according to the results, the topography and the amount of bed changes due to the process of erosion and deposition during the seasons are different in the two study areas. This is related to various factors such as grain size and bed slope. According to studies, the median diameter of sediments in the eastern regions has decreased compared to the western regions. This indicates the transfer of Caspian Sea sediments from west to east. In fact, in the western regions, due to strong sea currents and relatively coarse-grained sediments from the rivers of western Mazandaran, as well as human activities in those regions, the coasts have sediments with larger diameters than the eastern regions. Finally, finer sediments are transported, due to the weakening of the sea currents in the west to the east, so that their percentage has increased in the eastern regions. Also, the slope of the seabed has decreased in the eastern regions relative to the western regions due to the type and size of sedimentary grains and the effects of flow. Because of the weak flow and fine-grained sediments in the eastern regions, sediments settle and the depth decreases. As a result, the slope of the seabed has decreased in the eastern regions. The mentioned factors have caused differences in the intensity of erosion and sedimentation, followed by differences in the shape of the bed in the two beaches of Babolsar and Nowshahr during different seasons. Furthermore, considering the changes in coastal profiles during different periods, determining an equilibrium profile is important in the long-term study of beach profiles.

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