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The impact of rivers, ports, and coastal sediment transport on sediment distribution along the southern shore of the Caspian Sea

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ABSTRACT

The grain size distribution and mineral composition of coastal sediments vary along the shoreline and beach profiles. This variation depends on several factors, including the sources of the sediments (such as rivers), the distance from these sources, and the direction of littoral drift. Additionally, harbors and water intakes can lead to downstream erosion, which impacts the texture of the sediments. Understanding these changes is essential for comprehending littoral drift and the impact downstream from harbors and river mouths. Understanding these changes helps to better understand the littoral drift and the impact extent downstream from harbors and river mouths. This article analyzes data from 539 sediment samples taken from the southern shoreline of the Caspian Sea, across 94 beach profiles and at 6 different depths.The findings confirm a general eastward direction of littoral drift and identify a specific sediment cell (from Sefidrud to Anzali) where the littoral drift direction contradicts this overall trend. The study also reveals that the length of the eroded shoreline downstream of the Nowshahr and Amirabad harbors (which are 74 and 33 years old, respectively) measures 28 km and 14 km to the east. These results are supported by hydrographic maps at Nowshahr and satellite images indicating beach retreat at Amirabad. Furthermore, the affected shoreline near the Sefidrud River has been identified. The heavy minerals found in the studied area predominantly include magnetite, goethite, rutile, and zircon. The concentration of heavy minerals generally decreases from east to west, which aligns with the overall direction of sediment transport.

1. Introduction

The characteristics of sediment on different coasts are influenced by the properties of their sources and the processes involved in coastal sediment transport. The sediment found along various coasts differs in terms of its sedimentology and mineralogy. Engineering studies and numerical simulations take into account these differences both along the coastline and in perpendicular directions. This information also enhances our understanding of longshore sediment transport (LST) and cross-shore sediment transport (CST) patterns and also provides valuable field data for coastal engineering and environmental impact assessments of coastal structures.

Coastal sediment characteristics have long been of interest to researchers. Ward and Folk (1957), MacLaren and Bowles (1984), Van Mohtar et al. (2017), and Yang et al. (2024), conducted comprehensive analyses of the geometric parameters of grain size distribution by examining river and coastal sediments. Their findings revealed that coastal sediments become progressively finer as they move away from their source. The grain size distribution curve shifts towards finer particles, and the sorting index improves[1–4]. Friedman (1967), and Bing fu (2012), studied various sediment samples from coastlines and rivers. Their research showed that differences in transport mechanisms and sediment deposition between rivers and the sea lead to distinct patterns in grain size distribution. Specifically, the skewness of the grain size distribution curve for river sediments skews towards coarser particles, while marine sediments, particularly in the swash zone (the area where waves break on the shore), tend to exhibit finer particles.[5,6]. Gao and Collins (1992), Shandao (2012), Yun-pin (2015), Li et al. (2018), and Wang et al. (2023), By analyzing surface sediment samples from the shallow seabed and the river, researchers identified sediment transport trends at various points in a relatively complex environment through variations in grain size distribution. They noted that this method is limited to environments where grain size characteristics do not vary significantly and irregularly over short distances.[7–11].

Wang and Ki (1997), Cheng et al. (2009), Yamashita et al. (2018), and Muhardi et al. (2022), Using several sediment samples from cross-sections, researchers investigated the differences in sorting and skewness of sediment grain size curves at coastal locations and river mouths. They also examined the profiles related to erosion, deposition, and stability[12–15]. Duc et al. (2007), and Jiang et al. (2014), The researchers analyzed grain size curves from several collected sediment samples to study sediment transport both near and far from the coast. Their study revealed that sediment distribution and transport in this area are influenced by various factors, including river currents, coastal currents, waves, and the morphological characteristics of the delta. Specifically, they found that coarser sediments are more abundant near the river mouth, while finer sediments are prevalent in areas farther from the coast and in deeper waters. Additionally, they examined how different seasons, particularly high-flow and low-flow periods, affect sediment transport patterns[16,17]. Amalan et al. (2014), Perera et al. (2023), and Wickramasooriya et al. (2024), Gradistat software analyzed sediment samples collected from the coast and sea, focusing on mineral abundance and grain size characteristics to identify suitable sand and gravel deposits for construction after sediment washing[18–20]. Timothy (2016) investigated the impact of tidal range (6.6 meters) and waves on sediment sorting and grain size within the estuary and surrounding shores of the River Tamar in southwest England, comparing 80 surface sediment samples from riverbeds and coastal areas[21]. Pham et al. (2017) and Bandari et al. (2020) investigated the origin of the sediments by using surface sediments and obtaining geometric parameters, along with conducting XRD and XRF tests to determine the mineral types[22,23].

Studies on the relationship between coastal sediment characteristics and environmental conditions have been limited along the Caspian Sea coast. Khajeh et al. (2004), and Bahador et al. (2023 Coastal sediment samples from the southern Caspian Sea were analyzed, revealing that the average grain size and quartz content of sediments decrease from the northeast to the southwest, which aligns with the prevailing winds in the region[24,25]. Lashet Nasha'i et al. (2006), comparing surface samples from the Astara coast to the eastern part of Gilan Province in the Caspian Sea, showed that the direction of D50 reduction along the coast is aligned with the transport direction of coastal sediments[26]. Khoshravan et al. (2011), and Bagheri (2016) Using surface sediments along the Caspian Sea coast, researchers examined the mineralogy and geometric parameters. The results indicated that sediments from the western and central southern coasts of the Caspian Sea mainly originate from the Sefidrud River. It was shown that in areas with abundant heavy minerals, the seabed slope in shallow waters is steep, and the beach slope is moderate. Conversely, in areas with light minerals, the seabed slope is gentler, and the beach slope is steeper. In sections with coarse-grained sediments, both the seabed and beach slopes are steep. The coasts were categorized into three types: erosional, intermediate, and actively depositional[27,28]. MirKazemian et al. (2011), using 17 sediment samples from the sandy Babolsar coast to Nour and 16 samples from the Haraz River, identified the source of sediments as the upper Azarin massifs (basalt, andesite, and diabase) transported by the Haraz River to the coast[29]. Amini et al. (2012) studied 70 sediment samples from the Miankaleh and Neka coasts, showing that sediment transport strength decreases eastward along the coast and coastal hills transition from active to inactive[30]. Kiani and Afraideh (2012) found that reduced wave energy is associated with a decrease in the average grain size. They also highlighted the impact of human activities on sediment characteristics[31].

This study analyzed around 600 surface sediment samples collected from the southern coast of the Caspian Sea. The samples were compared based on their grain size distribution and mineral composition. Additionally, the research examined the effects of rivers, harbors, and other marine structures on the adjacent coastlines.

2. The study area

The research was conducted on the southern (Iranian) coast of the Caspian Sea, which has a shoreline length of 740 kilometers. This area is a remnant of the ancient Tethys Ocean surrounded by mountains formed from Late Miocene-Pliocene tectonic activity. Coastal sediments in the Caspian Sea are primarily influenced by river inputs, coastal erosion, wind transport, and biological processes. The mineral composition of the sediments is influenced by mountain erosion, river sediment transport, nearshore currents, and human activities. In recent decades, the Caspian Sea has faced significant challenges, including rapid water level decline, unsustainable development, sand extraction from the beach, and destruction of coastal habitats (see Fig. 1).

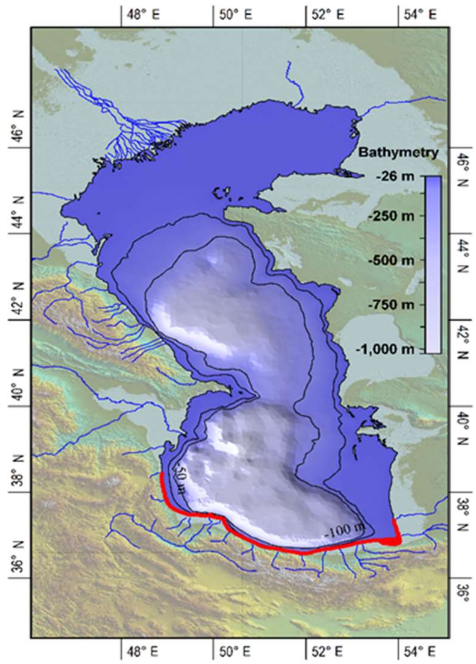

Figure 1: The location of the study area

3. Materials and Methods

3.1. Materials

A total of 539 sediment samples were analyzed from the shoreline and nearshore seabed up to a depth of 10 meters, along with 39 sediment samples from the most effective riverbeds leading to the sea. The sample collection took place from November to December 2013 and May to June 2014 by the Iranian Water Research Institute.

The sampling was conducted at 94 cross-shore profiles. Each profile was comprised of six sediment samples: one from the beach and the others from depths of 0.5, 1.5, 3, 6, and 10 meters. Additionally, three bed samples were collected from each river cross-section, including samples from the talweg, left bank, and right bank. The distribution of sampling sections can be seen in Figure 2. The sections for riverbed sampling were carefully selected to be sufficiently far from the river mouth and free from marine sediment influence, ensuring an accurate representation of the sediments entering the sea.

3.2. Methods

3.2.1. Grading

The sediment samples were analyzed at the laboratory of the Water Research Institute using sieve analysis. The hydrometer method was used for particles smaller than 0.063 millimeters.

The characteristics of grain size distribution curves of the samples have been compared using parameters such as mean (δ), sorting (M_Z), skewness (SK_G), and kurtosis (K_G). Formulas 1 to 5 were used to calculate the dimensionless grain size (ϕ) and the mentioned parameters. (Folk 1974[32]):

$$\varphi = -\log_2 d = -\ln d/\ln 2 \qquad 1$$

$$\delta = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6.6} \qquad 2$$

$$M_Z = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \qquad 3$$

$$SK_G = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2\,(\varphi_{84} - \varphi_{16})} + \frac{\varphi_5 + \varphi_{95} - 2\varphi_{50}}{2\,(\varphi_{95} - \varphi_5)} \qquad 4$$

$$K_G = \frac{\varphi_{95} - \varphi_5}{2.44\,(\varphi_{75} - \varphi_{25})} \qquad 5$$

The shape indices of the size distribution curve are useful in determining the origin of sediment. For example, the skewness parameter, which measures the departure from symmetry in grain size distribution, indicates whether there is an excess source of finer or coarser particles. Coastal and riverine sediments are typically categorized according to Tables 1 and 2[33].

The grain size distribution curve of coastal sediments generally falls within the moderate to good sorting range, while dunes are characterized by good sorting. River sediments, on the other hand, usually exhibit moderate to very poor sorting[32].

Coastal sediments usually have a negative skewness value in their grain size distribution, while aeolian (wind-blown) sediments tend to have positive skewness values. River sediments, exhibit skewness toward coarser particles[34].

There is a direct relationship between kurtosis and sorting, with higher kurtosis corresponding to better sorting[35]. Beach sands typically exhibit moderate to well-sorted kurtosis, while aeolian dunes fall within the well-sorted to very well-sorted range. River sediments tend to have broader kurtosis[36].

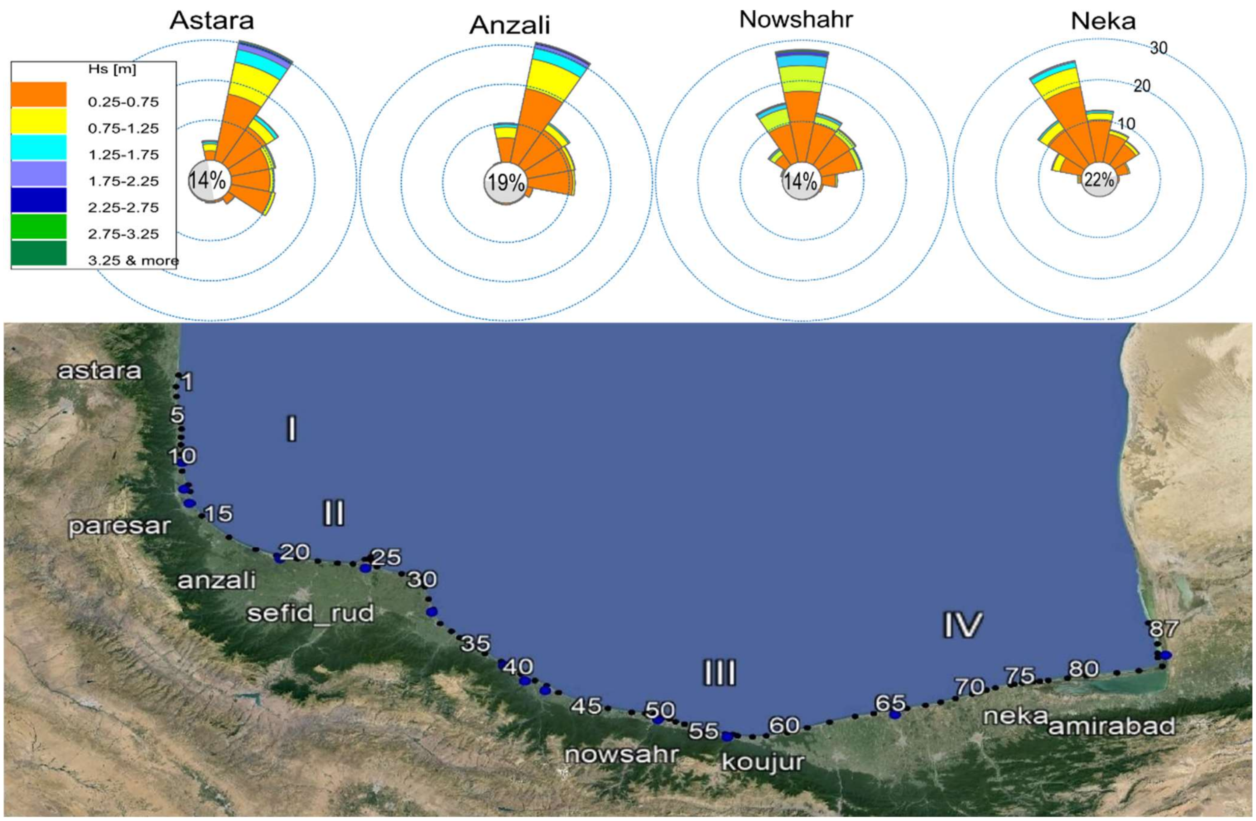

Figure 2: Location of surface bed samples and wave roses affecting the area

Table 1: Sorting and kurtosis classification[32]

Sorting		kurtosis	
Very well	>0.35	Very platykurtic	<0.67
Well	0.5-0.35	Platykurtic	0.9-0.67
Moderately well	0.7-0.5	Mesokurtic	1.11-0.9
Moderately	1-0.7	Leptokurtic	1.5-1.11
Poorly	2-1	Very leptokurtic	3-1.5
Very poorly	4-2	Extremely leptokurtic	> 3

Table 2: Classification of skewness[32]

Strongly fine_skewed	+1 - +0.3
Fine_skewed	+0.3 - +0.1
Near_symmetrical	+0.1 - -0.1
Coarse_skewed	-0.1 - -0.3
Strongly coarse_skewed	-0.3 - -1

3.2.2. Mineralogy

A Nikon (Eclipse E100) microscope with a 100X zoom scale was utilized to classify minerals in bed samples in the University of Qom's laboratory. Each sediment sample was photographed under the microscope, and the number of grains for each mineral in each sample was determined through visual counting. The percentage abundance of each mineral was calculated by dividing the number of grains for that mineral by the total number of grains. Figure 3 shows an example image of the collected sediment[37].

Figure 3: Microscopic image of a sample (100X) (Location: profile # 2-deph 1.5m)

4. Results and Discussion

The amount of minerals in sediment samples varies along the shoreline and by the water depth. The reason is difference in distance and direction from the sediment sourthes (ie river mouths) and the density/strength difference of different minerals. The amount of heavy minerals changes significantly along the studied coastline. The heavy minerals are pyroxenes, augite, diopside, magnetite, goethite, tourmaline, pyrite, hematite, garnet, ilmenite, rutile, and zircon.

The grain size distribution of the sediment samples varies along the studied coastline. There is a general trend along the coastline and also some local variations near large rivers and harbors. The grain size distribution variations along the coastline are used to verify the dominant LST direction and to determine the impact zone of coastal structures and river mouths.

4.1. The general trend

Figure 4 illustrates the relative abundance of heavy minerals in collected sediment samples. It shows that heavy minerals are more prevalent along the western and central shorelines, compared to the eastern coasts. Here the mountains are near the sea. The rivers originate from mountainous regions and the bed slope along their entire path is steep, with no mild slope area to deposit the heavy minerals or larger grain sizes. These rivers transport a greater amount of heavy minerals to the shore. In contrast, eastern rivers contribute fewer heavy minerals to the coast. For instance, the Gorganrud River, located in the easternmost section, carries quartz-rich sediments without significant heavy minerals into the sea. The trend of decreasing heavy minerals aligns with the dominant littoral drift direction from west to east. Heavy minerals are less associated with littoral sediment transport compared to other grain sizes. Additionally, Figure 4 shows that the variation in heavy mineral abundance with depth, decreases along each section as we move eastward. Decrease in the intensity of waves and the presence of heavy minerals play a role in this regard.

Figures 5 and 6 illustrate the mean and sorting parameters of the grain size distribution for the sediment samples (see formulas 2 & 3). The two graphs shaw that the sediments are predominantly fine sand, and their sorting parameter falls within the moderate to good range. Considering Figure 2 for sample locations, the graphs reveal that in mountainous coasts, sediments at the shoreline and half-meter depth are much coarser than other depths. For these coasts, the sorting parameter is also much lower at the shoreline and half-meter depth compared to the other depths.

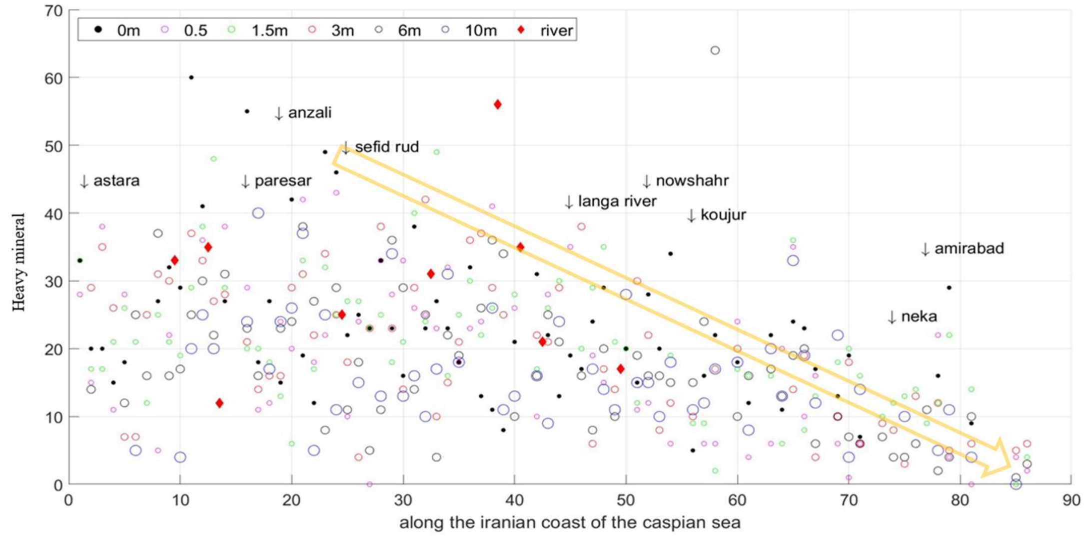

Figure 4: The abundance of heavy minerals in sediment samples.
(The horizontal axis indicates the section numbers in Fig. 2)

On the easternmost coast, where fine-grained sediment-rich rivers flow into the sea, sediment grain size is much smaller at all depths (both inside and outside the surf zone) compared to other coasts.

The studied coast along the Caspian Sea can be divided into three categories and five sections:

A) From sections 1 to 16 (Astara to Paresar) and from sections 35 to 61 (Kelachay to Khoshtsar), where the shoreline is near the mountains with mountainous rivers and coarse beach sands, exhibiting moderate to very poor sorting.

B) From sections 16 to 35 (Paresar to Kelachay) and from sections 61 to 83 (Khoshtsar to Miyankaleh), where the coastlines are far from the mountains, with sediments on the shoreline relatively similar to the entire surf zone.

C) From sections 83 to 87 (Gomishan coast), with very fine silty sediments on the coastline and the entire surf zone and beyond. The bed slope is extremely gentle due to the long-term influence of the Gorganrud and Atrak rivers, which pass through dry regions with a very low slope, carrying very fine sediments into the sea. The sorting of sediments in this region is also severely poor and distinct from other studied areas.

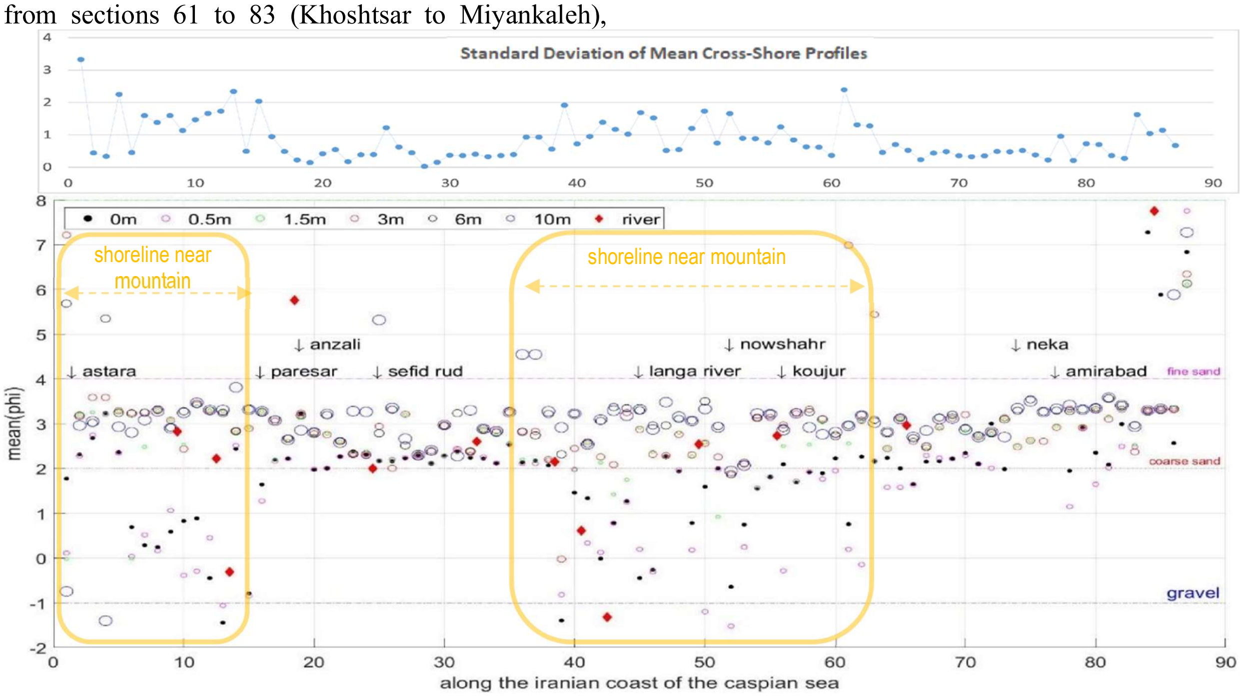

Figure 5: The mean grain size along the studied shoreline at different water-depths and the standard deviation of the mean parameter along each profime (The horizontal axis indicates the section numbers in Fig. 2).

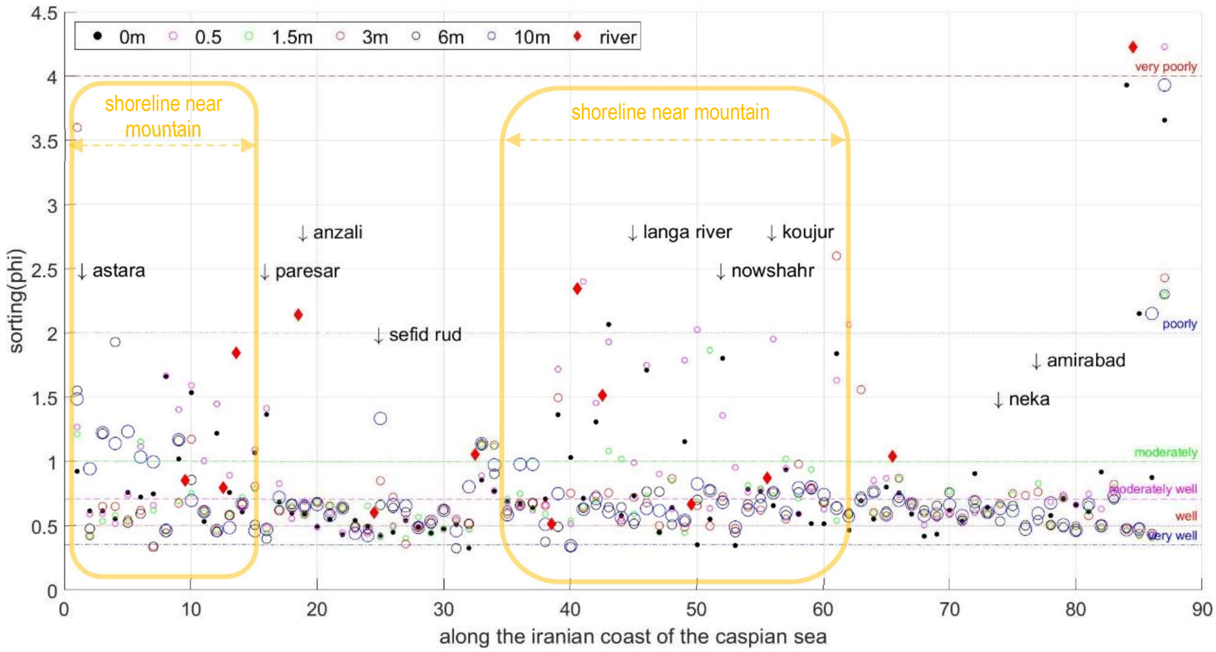

Figure 5: The sorting of grain size distribution along the studied shoreline at all inquiried water-depths (The horizontal axis indicates the section numbers in Fig. 2)

4.2. The direction of littoral drift

Considering the prevailing wave directions and shoreline angles shown in Figure 2, sediment transport along the southern coasts typically occurs from west to east or north to south. However, there is one exception: along the shoreline sections 18 to 25 depicted in Figure 2, the direction of LST is from east to west (see Fig. 7). This section of the shoreline constitutes a distinct sediment cell. The eastern boundary of this cell is marked by the mouth of the largest river in the study area, while the western boundary corresponds to the edge of a large bay that existed four centuries ago (as indicated by historical maps and travelogues) and is currently located near the entrance of a significant estuary.

An analysis of grain size variations along the studied coastline supports the aforementioned transport directions. For example, Figure 8 illustrates that the sand becomes progressively finer as one moves from section 25 (the river mouth) toward section 18, with no significant changes in coastal morphology. In the absence of any intervening factors, it is expected that sediment grain size along the coastal transport path will gradually decrease. This occurs because finer sediments are lighter and are more easily moved by littoral currents.

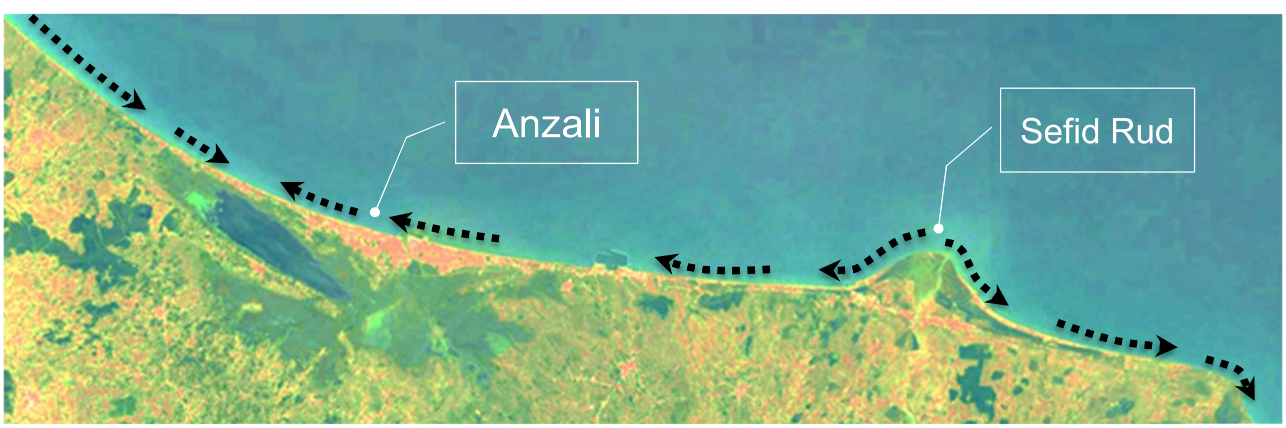

Figure 6: Satellite images of the area from Anzali to Sefidrud (Google Earth)

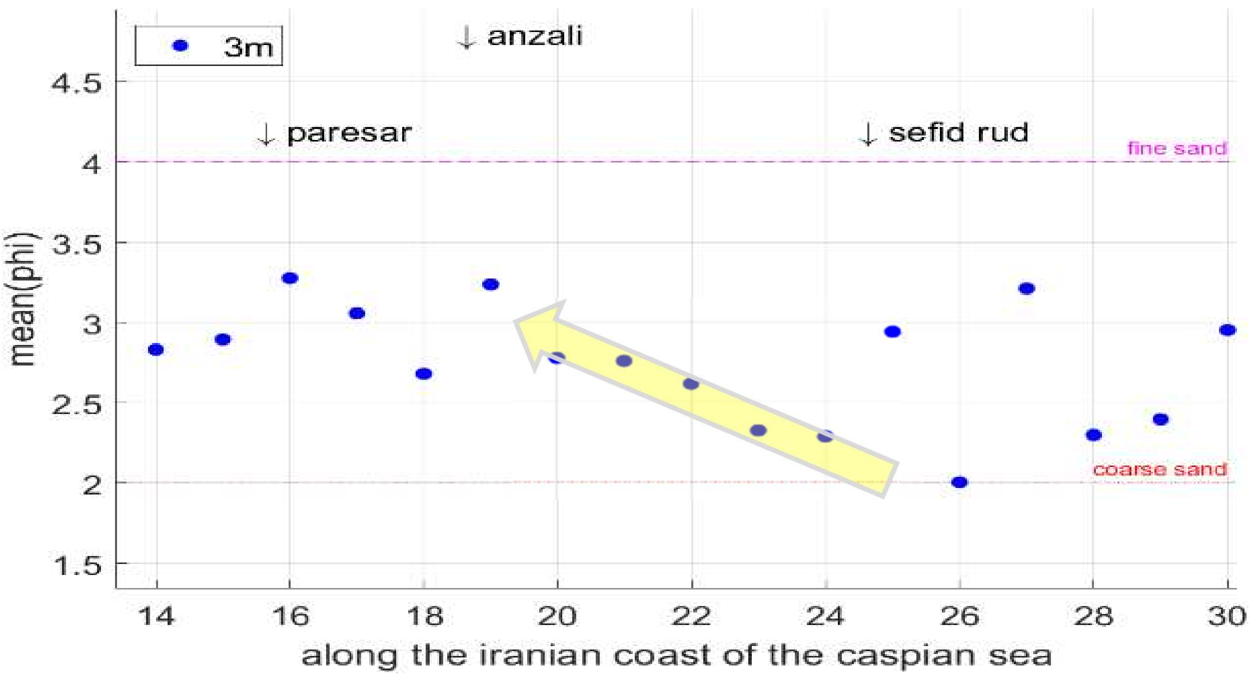

Figure 7: The mean grain around Anzali and Sefidrud shorelines at a depth of 3 meters

4.3. The impact zone of rivers and harbors

Studying the changes in grain size distribution along the coast is essential for understanding the length of coastline sections influenced by sediment-supplying rivers and large harbors that interrupt littoral drift.

Sediment-fed rivers disrupt the gradual variations in grain size distribution along the LST direction, as they introduce sediment with grain sizes that differ from those typically found along the shoreline. Similarly, large harbors alter coastal sediment dynamics by interrupting the natural transport of littoral sediments. Downstream of these harbors, waves are more effective at carrying finer and lighter grains, while there is no supply of replacement sand from upstream. This leads to a shift towards coarser sediments and heavier minerals.

This section analyzes sediment samples collected at depths of 1.5 and 3 meters, as the primary LST occurs within the nearshore area at depths ranging from 1.5 to 4 meters. Figures 9 and 10 illustrate the mean and sorting parameters, respectively.

The analysis focuses on two coastal structures and two river mouths. The selected harbor is Nowshahr Harbor, located at section 51, while the Neka-Sadra-Amirabad complex, which includes two water intakes and two harbors, is assessed at sections 73 to 76. The river mouths examined are the Sefidrud River at section 25 and the Atrak-Gorganrud River at sections 84 and 87.

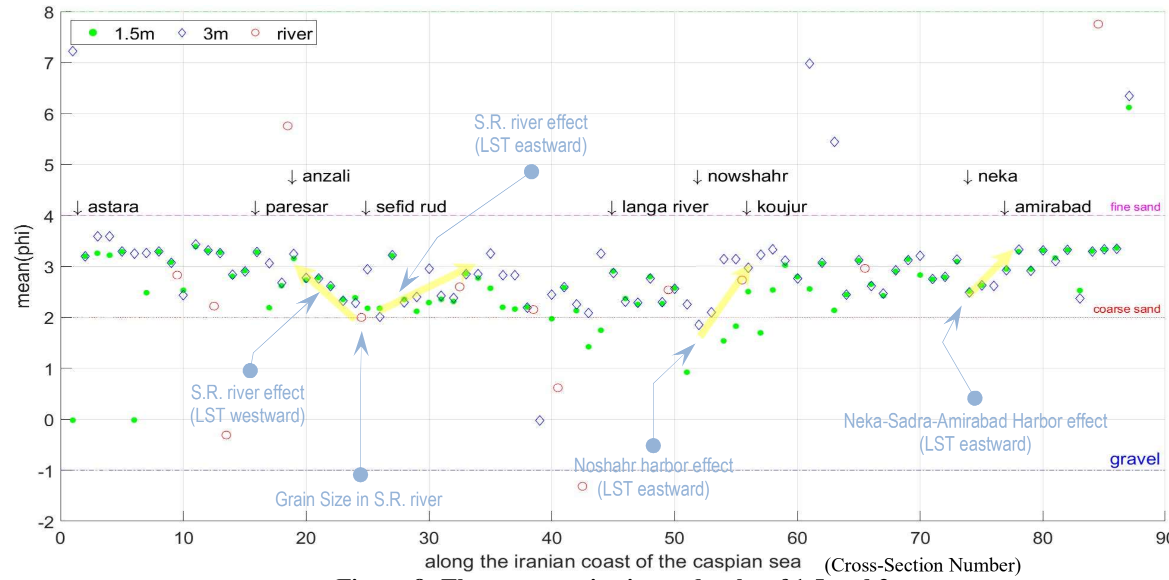

Figure 8: The mean grain size at depths of 1.5 and 3 meters
(The horizontal axis indicates the section numbers in Fig. 2)

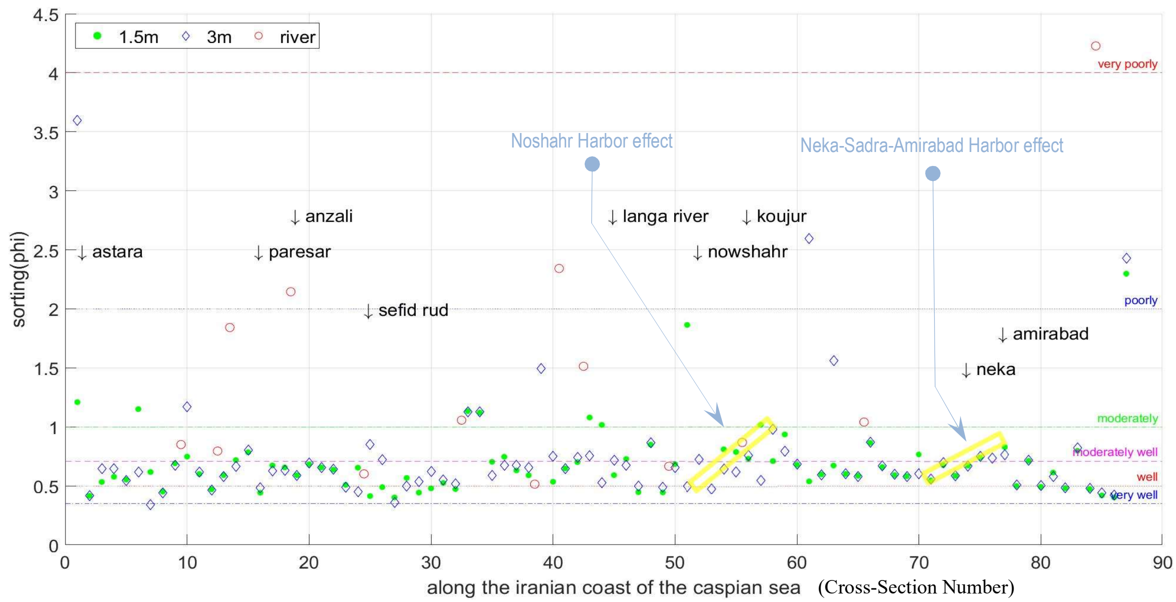

Figure 9: The sorting of grain size distribution at depths of 1.5 and 3 meter
(The horizontal axis indicates the section numbers in Fig. 2)

4.3.1. Nowshahr Harbor

Nowshahr Harbor (section 51) was constructed between 1929 and 1939, with its entrance located 900 meters from the initial shoreline. The dominant LST direction in this area is eastward. Over the past 85 years, the harbor has prevented the surf-zone sand from reaching the eastern beach. There are no significant sediment-supplying rivers to the east of the harbor (see Fig. 11).

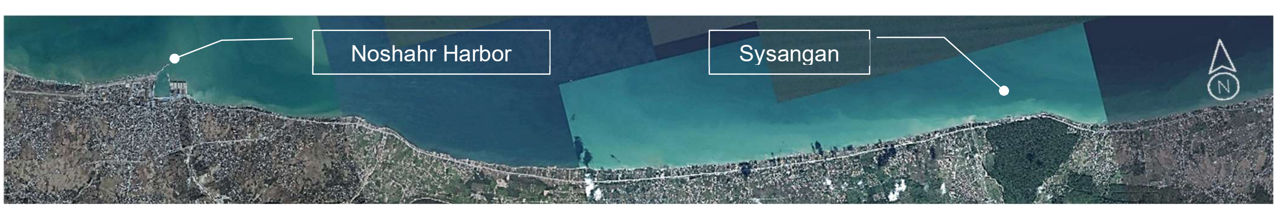

Figure 10. Satellite images of the shorline from Nowshahr Harbor to Sysangan (Google Earth)

Figure 9 illustrates that the sediment size on the eastern shore is much coarser than that on the western coast, a difference attributed to erosion occurring on the lee side of the harbor. As one moves further east to section 56, the coarseness of sediment gradually decreases, aligning more with the general trend in the area. This indicates that Nowshahr Harbor has affected approximately 28 kilometers of the downstream beach as of the sampling year of 2011.

Figure 12 reveals the surf-zone bathymetry downstream of the harbor (sounding date: 2005). It shows that the 2-meter depth contour line is very close to the shoreline, only 15 to 30 meters away, for up to 23 kilometers downstream of the harbor. Beyond this point, the distance increases to between 120 and 200 meters. The length of the eroded beach, determined by grain size comparison (28 km), aligns reasonably well with the result obtained from surf zone hydrography (23 km). The discrepancy is only 15%, while sediment sampling and grain size comparison method is more cost-effective than beach profiling.

The coastal land east of Nowshahr Harbor consists of hard soil that does not erode easily due to wave action. Consequently, satellite imagery does not provide useful information for identifying the eroded zone.

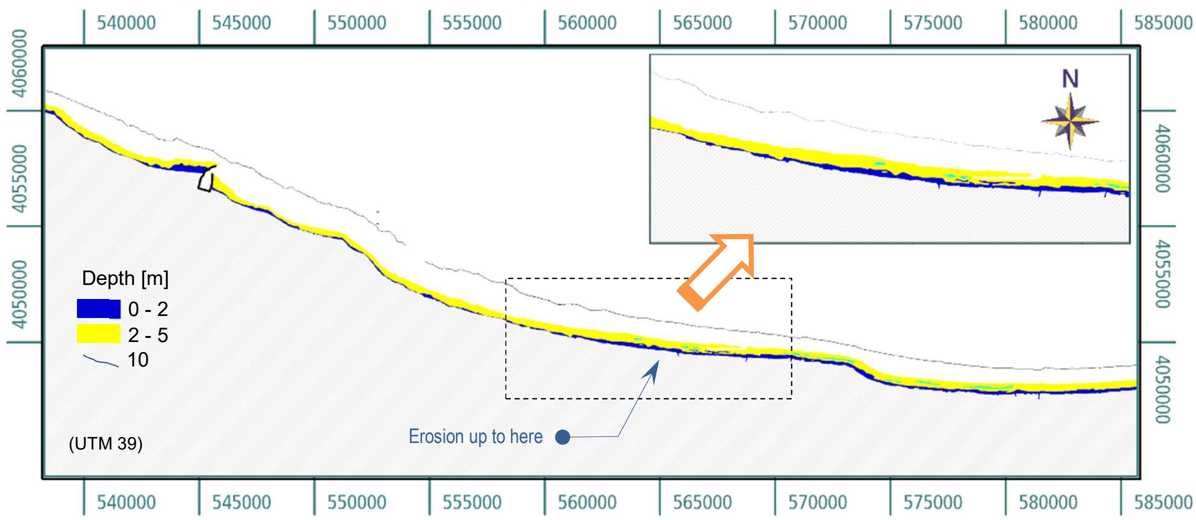

Figure 11: The 2 and 5-meter depth contours along the coast from Nowshahr to Sisangan, based on the measurements conducted by the National Cartographic Center in 2005

4.3.2. Neka-Sadra- Amirabad complex

The Neka power plant has two water intakes and is located near the Sadra harbor at section 73, with another harbor situated 8 km to the east at section 76. These facilities were built between 1977 and 2005 and extended between 800 to 2000 meters from the original shoreline (refer to Fig. 13). In this region, the LST direction is eastward. The presence of these structures disrupts the natural LST, leading to erosion along the eastern shorelines.

Figure 12: Satellite images of the area from Neka to Amirabad (Google Earth)

Figure 9 illustrates how the Neka-Sadra complex has resulted in a sudden increase in sediment grain size due to erosion at section 73. As one moves eastward away from Sadra toward section 78, which is located downstream of the Amirabad harbor (section 76), the grain size gradually decreases. This indicates that the area impacted by erosion from Amirabad harbor merges with the impact zone of the Neka-Sadra complex. The erosion in this region has also caused a slight decline in the sediment sorting index from Sadra to Amirabad harbors (see Fig. 10).

The irregularities in grain size and sorting observed conclude after section 78. This signifies that the total area affected by erosion from the Neka-Sadra-Amirabad facilities spans approximately 14 km (from section 73 to section 78), which corresponds with findings from satellite imagery.

Interestingly, the grain size on the lee side of Amirabad harbor is not coarser than that on the upstream (west) side. This is because a significant portion of the materials dredged during construction was deposited on the eastern coast, which is then eroded by larger storms along the shoreline. As a result, there is a sediment source to replace the finer particles of the eroded materials from the surf zone.

4.3.3. Sefidrud River

The Sefidrud River, located at section 25, is the largest river flowing into the Iranian shores of the Caspian Sea. As shown in Figure 9 (see section 25), the sediment carried by the river is coarser than that of the surrounding shoreline. This coarser sediment greatly influences the grain size in the surf zone of the sea.

Moving away from the river mouth, the sediment grain size decreases on both sides (from section 25 to section 18 and from section 25 to section 35). This decrease is due to the direction of sediment transport being away from the river mouth. Interestingly, the sediment transport path from the Sefidrud mouth to Anzali (section 25 to section 18) is the opposite of what is generally observed along most southern Caspian shores, which typically transport sediment from west to east (see Fig. 7).

Based on the trend lines in Figure 9, the river's sediment supply significantly affects the sediment grain size distribution along the western and eastern shorelines, extending up to 43 km and 68 km, respectively. An anomaly observed at section 30 is attributed to a local river mouth, known as RoodSar.

At section 18, there is an estuary inlet that serves as the entrance to Anzali harbor. The river associated with this inlet carries fine-grained sediments; however, the majority of these sediments settle either inside the estuary or within the harbor basin. Consequently, they have minimal impact on the sediment texture in the surf zone on both sides of the inlet. The wash load and remaining cohesive materials that are released into the sea cannot settle in the surf zone due to wave action.

4.3.4. Gorganrud and Atrak Rivers

The Gorganrud River (section 84) and the Atrak River (near section 87) flow into the southeastern corner of the Caspian Sea (see Fig. 9, section 84). The mouth of the Gorganrud River is located precisely at the corner, while the mouth of the Atrak River is situated 20 kilometers to the north. The LST direction on both sides is towards this corner. The Atrak River carries very fine-grained sediments to the sea. In this region of the Caspian Sea, the coastal and seabed slopes are quite gentle. The distance from the shoreline to a depth of 30 meters is approximately 50 kilometers, and the maximum slope of the seabed is less than 0.1%. As a result, large waves do not reach the nearshore area in this part of the Caspian Sea

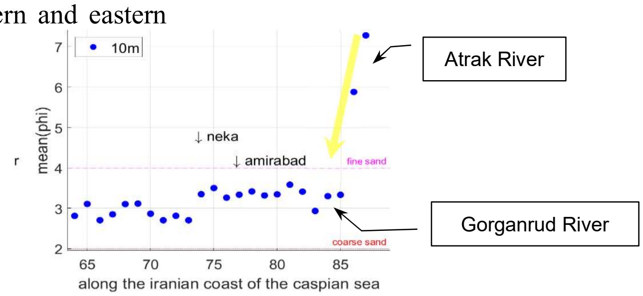

Figure 13: The mean grain size off the south-eastern shoreline (at a depth of 10 meters)

5. Conclusions

Sediment texture along the southern (Iranian) shores of the Caspian Sea has been analyzed using approximately 600 sediment samples collected from nearly 90 beach profiles, with six samples taken from both inside and outside the surf zone along each profile. The differences in sediment samples were examined in both the longshore and cross-shore directions from sedimentological and mineralogical perspectives. The study highlights the impact of sediment supplies from rivers and the erosional effects of harbors, which have contributed to changes in sediment texture along the southern Caspian coast.

This research specifically focuses on variations in three selected indices: mean grain size, sorting, and abundance of heavy minerals. These indices were used to assess sediment transport directions and the influence zones of major rivers and harbors.

The findings confirm a general trend of eastward LST direction, except for the Anzali-Sefidrud shoreline, which is identified as a distinct sediment cell with LST directed westward. A shift in the LST direction occurs at the mouth of the Sefidrud River.

Additionally, the study demonstrates that the erosional impact zones for Noshahr harbor and the Neka-Sadra-Amirabad complex extend approximately 27 and 15 kilometers eastward, respectively. The influence zone of the Sefidrud River mouth within the surf zone spans about 68 kilometers to the east and 43 kilometers to the west.

Attempts were made to estimate the closure depth based on the variations in sediment sample characteristics inside and outside the surf zone. However, a specific criterion for distinguishing sediments in these two areas was not established. This may be due to the limited number of sediment samples collected along each profile or the historical changes in sea level, which included a decrease of approximately 3 meters, followed by an increase of 2.5 meters, and a further decrease of 2 meters within a century.

Acknowledgements

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