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## Southern Caspian Sea Coasts, Morphology, Sediment Characteristics, and Sea Level Change

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## PART V: Sediments

### Chapter 11

## SOUTHERN CASPIAN SEA COASTS, MORPHOLOGY, SEDIMENT CHARACTERISTICS, AND SEA LEVEL CHANGE

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### ABSTRACT

As the world's largest closed body of water, considerable changes in the Caspian Sea water level make it an unique laboratory to study all aspects of coastal zones. This research was aimed at evaluating the linkage between sea level changes and sediment characteristics of the south Caspian Sea coast. Initially, three field surveys were made along 700 km of the southern Caspian Sea coast. In addition to nearshore sampling, land forms were mapped. On the basis of the field reconnaissance, eight principal sampling stations were chosen. Sediments were sampled by divers along profiles at right angles to the coast at 5 depths (2, 4, 6, 8, 10 meters). Hydrographic profiles also were surveyed. Laboratory tests on the sediment samples were made, and the sediment characteristics and morphological features were divided into distinct zones based on their response to sea level changes.

Keywords: Caspian Sea, water level changes, sediment characteristics, sampling, morphology

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## **1. INTRODUCTION**

The Caspian Sea is the largest closed body of water on Earth with a surface area of around 380,000 km<sup>2</sup> and a volume of about 78,000 km<sup>3</sup>. This volume accounts for approximately 40% of the world's lake waters (Kaplin and Selivanov, 1995). It is believed to be a remnant of the Tethys Ocean that became landlocked about 5.5 million (MM) years ago due to plate tectonics (Kroonenberg et al., 2007). Five different countries border this sea, namely Iran, Turkmenistan, Kazakhstan, Azerbaijan and Russia (Fig. 1). This sea measures around 1,180 km North-South (between latitudes 36° and 47°) and as much as 480 km East-West (between longitudes 49° and 54°). It has no tides, and its salinity (5 to 13 gr/ litre) is only approximately one third of that of the open oceans, increasing from the north, where the Volga River flows into the sea, to the south (Peeters et al., 2000).

The Caspian Sea can be considered as having three parts (Froehlich et al., 1999; Kaplin and Selivanov, 1995): a northern part, with a mean water depth of only 10 m; a central part, where the water depth increases up to 788 m; and a southern part, wherein the water depth increases up to 1025 m.

A range of small and large rivers feed the Caspian Sea mostly from the south, west, and north and variations in their discharge can significantly affect the water volume and therefore the water level.

The considerable drop in the Caspian Sea level began in 1930. Prior to that the observed water level had been more constant, fluctuating around -26 m for about eight decades. In 1929, the water level stood at 26.1 m below open oceanic levels. This level dropped rapidly by around 1.6 m and reached -27.7 m by 1940. After that the Caspian's sea level continued to decline but at a slower rate, falling by around 1.4 m within 37 years and reaching -29.1 m by 1977. After 1977, the sea level suddenly began to rise such that a water level of about -26.7 was recorded in 1995 showing an increase of 2.6 m over the period 1977 to 1995. Since 1995, a slow rate of decline has occurred.

Historical repeated water level oscillations in the Caspian Sea, mostly interpreted from sedimentary deposits, have been the subject of several research studies. For example, biostratigraphical and radiometric investigations of the Kura Delta and its Holocene deposits show a repeated alternation between deltaic and marine environments. The changes resulting from high frequency changes in the Caspian Sea surface level representing four episodes of delta progradation followed by erosional transgressive surfaces (Hoogendoorn et al., 2005). The Volga Delta was also surveyed by Kroonenberg et al. (1997) and five magnitudes

(phases?) were recognized through stratigraphical studies for the Quaternary Caspian Sea water level variations. The authors found that a highstand (Caspian Sea level reached 50 m above global sea level) in the early Pleistocene linked the Caspian Sea and the Black Sea. As another example, lagoonal deposits and barrier-lagoon systems, as well as deltaic deposits, suggest past oscillations in the Caspian Sea. Kroonenberg et al. (2007) studied the Holocene barrier along the Dagestan coast and found that the last notable highstands took place around 2600 BP.

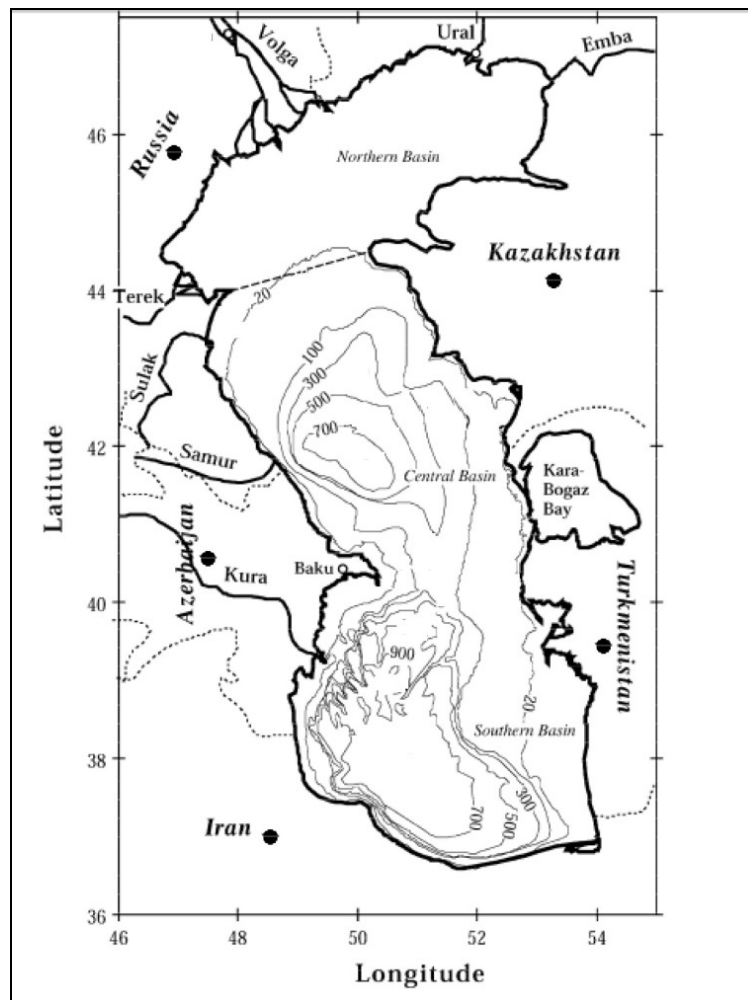


Figure 1. The Caspian Sea bathymetry, bordering countries, subbasins, and major rivers (After Peeters et al., 2000).

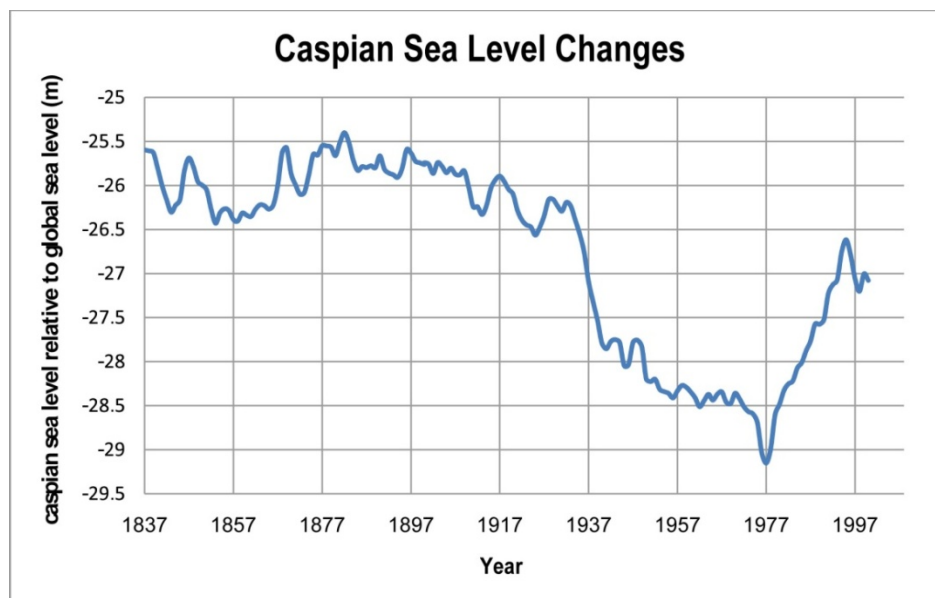


Figure 2. The Caspian Sea level fluctuations during the 20th century (Data based on Baltic Sea level).

The causes of fluctuations in Caspian Sea level are not yet entirely clear (Kroonenberg et al., 2007; Boomer et al., 2005). Most studies, however, emphasize climate change and anthropogenic factors (Shiklomanov *et al.*, 1995), rather than geological and tectonical effects (e.g., Rychagov, 1997; Golitsyn, 1995). Aspects of Caspian Sea level change have been the subject of various research studies related to hydrology, geomorphology, and biology, but the effect of these changes on the seismic regime in the Caspian Sea region has not been studied in detail. The recent Caspian Sea level changes have created a new system of beach deposits and profiles. While these coastal evolutions under conditions of sea level change have been studied on the northern and western Caspian Sea coastline (Kaplin and Selivanov, 1995; Kroonenberg et al., 2007; Kroonenberg et al., 2000), the southern Iranian Caspian Sea coast has not been adequately explored. The present research investigated the impact of the 20<sup>th</sup> century changes in Caspian Sea level on the Iranian Coast of the Caspian Sea.

## 2. SEA LEVEL VARIATION AND COASTLINE CHANGES

Prediction of coastal changes related to sea level changes is fraught with difficulties. Predictive models are not being reliably generated due to a lack of knowledge of the interaction between coasts and energy sources. On the other hand, a model which is developed to forecast the behaviour of a particular coast cannot be applied to another because natural processes depend on coastal features

which differ from one coast to another. Bruun (1962) proposed that the equilibrium beach profile does not change in response to sea level variations (Bruun Rule), and in the case of sea level changes only a given volume of sand will move from the upper part of the profile. This volume of sand will lie over the lower part of the profile, and the accumulated volume is equal to the eroded volume (Fig. 3).

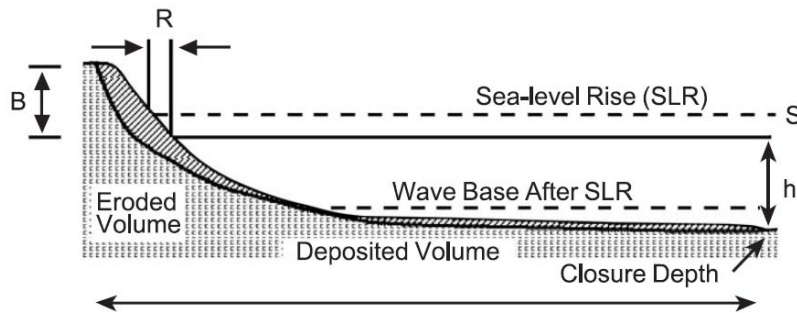


Figure 3. Shoreline erosion under rising sea level conditions, the Bruun Rule (Cooper and Pilkey, 2004).

Based on the Bruun Rule, since the shore-normal geometry of beaches remains unchanged under sea level rise conditions, the amount of shoreline retreat can be calculated if the amplitude of sea level rise and the form of the original profile are known. This geometric model can be applied if assumed geometric rules are valid. Cooper and Pilkey (2004) concluded that the Bruun Rule does not work and should be abandoned for three reasons.

First, there are some assumptions which cannot be found in nature. For example, longshore transport is omitted in this two dimensional model. Second, this rule ignores some main variables such as particle sizes existing on beaches, bottom currents, and bedforms. Finally, the concepts providing the foundation for the Bruun Rule are known to be outdated.

Leatherman et al. (2000) confirmed the Bruun Rule by modelling a number of coasts, for example the New Jersey coast in the United States. However, their claim was very soon rejected by Sallenger et al. (2000) and Pilkey et al. (2000) who claimed that the data had been selected with a view to validating the Bruun Rule.

The aforementioned critical study of Cooper and Pilkey (2004) is convincing because they evaluated almost all studies conducted on the Bruun Rule. Furthermore, Kaplin and Selivanov (1995) estimated shoreline retreat for three depositional coasts of the Caspian Sea over the period of the Caspian Sea level rise. Their study showed overestimations of up to 600 percent by the Bruun Rule.

For instance, field data showed a 20-25 m shoreline retreat on the Lenkoran coast of Azerbaijan, but the Bruun Rule estimated it at around 130-150 m. Even with some modification, this estimation only decreased to around 90-105 m.

The effect of sea level change on coastal morphology is based on reconstructions, not on real time observations. These are troublesome because the rate of present sea level change is so slight (about 10-20 cm per century, the present sea level has an upward trend, and the last lowstand deposits can only be investigated by drilling or deep sounding and other similar methods. It is necessary to validate numerical models using real time data, and laboratory simulations are hindered by drawbacks such as downscaling (Kroonenberg et al, 2000). While the linkage between sea level changes and coastal landforms has not yet been completely understood (Cooper and Pilkey, 2004) the Caspian Sea can play an important role in enhancing our knowledge of coastal behaviours in response to sea level variations. This is because of its significant water level changes and approximately 7,000 km of coastline are available for investigation.

The Caspian Sea as the best natural laboratory for studies related to coastal response to sea level changes. Present coasts of the Caspian Sea were formed in response to its repetitive level variations during the New Caspian transgression which began 8,000 yrs B.P. These coasts can be classified into four categories (Kaplin and Selivanov, 1995): mud flats; depositional coasts composed of bars, spits, etc.; erosional coasts; and deltaic coasts. The Caspian Sea possesses all of the different coastal types which can be found along the world's coastlines and these coasts show different behaviour in response to sea level changes.

### **3. THE CASPIAN SEA COAST UNDER RECENT WATER LEVEL VARIATIONS**

The Caspian's various coastal types were introduced in the previous section. Their responses to Caspian Sea level changes are discussed in this section.

#### **3.1 Mud flats**

Mud flats tend to lie beside the lowland areas, stretched along the northeastern, southeastern corner, and northwestern coasts of the Caspian Sea during the period of Caspian Sea level fall from 1930 to 1977. Also, in this period, mud flats surrounded all bays of the Caspian Sea including Kirov Bay, Krasnovodsk Bay, Kizlyar Bay, and Komsomoletz Bay, though the rate of shoreline migration differed. For example, the shoreline of Kizlyar Bay advanced by 150-200 m/yr while the rate of shoreline migration in Komsomoletz Bay was 700-800 m/yr (Kaplin and Selivanov, 1995).

### **3.2 Depositional coasts**

The period during which the Caspian Sea level showed a decreasing trend is marked by an increase in the size and volume of depositional bodies such as dunes, barriers, and spits, except those which were being supplied by cliff erosion. In this period cliffs were inactive resulting in a decrease in longshore drift causing erosion to spits. On the coasts where nearshore slope was relatively gentle (tangent slope 0.0005-0.005), landward migration of these bodies occurred while their geometry remained almost unchanged (Kaplin and Selivanov, 1995). Moderate nearshore bottom slopes (tangent 0.005-0.01) usually mark barrier coasts (Roy et al., 1994) and under the Caspian Sea level fall its barriers increased their width and volume. Under rising sea level conditions however, sand ridges emerged on the coasts and a rise in the groundwater table formed a lagoon behind the ridges. On the coasts with a steep backshore (tangent slope over 0.03-0.05) lagoons did not form. Steep nearshore bottom slopes (tangent slope over 0.01) caused intensive erosion to beaches leading to the formation of scarps of up to 1-1.5 m (Kaplin and Selivanov, 1995). Barrier coasts were comprehensively studied by Kroonenberg et al. (2000), who investigated the barrier coast of Kaspiisk in Russia at the western Caspian Sea coast which had been monitored during the period of recent Caspian Sea level changes.

### **3.3 Deltaic coasts**

When the sea level began to decrease a passive emergence occurred on the deltaic coasts. The Kura delta and the Sulak delta expanded up to 50-60 and 100-200 m/yr, respectively. The Volga delta together with the Ural delta located on the northern Caspian Sea coasts experienced a considerable expansion and caused the shoreline to move ahead by hundreds of kilometres. When the trend reversed and the Caspian Sea level started to increase, the deltaic shorelines retreated. The rate of the shoreline retreat was not as much as the shorelines' advance in some deltas. While some areas were completely inundated the Volga delta retreated by only 2-4 m/yr. A main reason for this was the increase in sediment discharge. It is suggested that Volga sediment discharge increased by 33 percent due to an increase in its water discharge during the 1980s (Kaplin and Selivanov, 1995). Volga sediment discharge is composed of silt, clay, and very fine sand forming a gently sloping coast. Sea level rise and increasing Volga discharge worked together to vertically grow sediment bodies while sea level fall increased channel erosion leading to fast shoreline advances (Kroonenberg et al., 1997). The maximum level that the Caspian Sea experienced during the past century was 25 m below global sea level and it has been suggested that it may increase to near the



original level again, in which case a wide area will be inundated (Li et al., 2004). The present day Kura delta is composed of sandy and clayey bodies. The aggradation process, during the period of water level increase in the Caspian Sea resulting from flooding of the Kura River delta, and progradation over the period of sea level fall, both control the Kura River delta as much as do river dynamics (Hoogendroon, 2005).

### **3.4 Erosional coasts**

Erosional coasts can be observed in the coasts of Azerbaijan, Russia, Kazakhstan, and Turkmenistan. During the period of sea level fall the cliffs were left behind and cliff erosion ceased because the causative waves broke over the newly emerged area. When this area was submerged again by an increasing sea level, erosive waves attacked the cliffs and the result was an increase in the length of the erosional coasts of the Caspian Sea such that, for example, in Azerbaijan there was an increase from 20 to 55 percent in length along the whole coastline (Kaplin and Selvianov, 1995).

## **4. SOUTHERN COASTS OF THE CASPIAN SEA UNDER WATER LEVEL VARIATIONS**

These segments of coastline, similar to other coasts, had appropriate responses to the sea level changes but published data is in relatively short supply (Kazanci et al., 2004). These coasts can be morphologically categorized into five zones. The morphodynamics of each zone were characterized to evaluate vulnerability of beaches and for hazard assessment by Khoshnavan (2007) and hazardous areas were marked. His study showed that nearshore slope, shore morphology, and sediment characteristics vary along the southern Caspian Sea coastline. There exist several lagoons and bays along the Southern Caspian coast the most important ones being Anzali lagoon in the west and Gorgan Bay in the east (Fig. 4). The recent Caspian Sea level rise, which occurred between 1977 and 1995, doubled the Anzali lagoon surface from 80 to 160 km<sup>2</sup> (Kazanci et al., 2004). The Alborz mountain range governs the shore width throughout the coastline and the rivers feeding the Caspian Sea from the south contribute great amounts of sediment to the shores to expand their width.

In the east, where the coast is composed of fine grain sediment, waves are prevented from reaching the shore due to the gentle slope of the nearshore zone. Sandy beaches stretch along the hundreds of kilometers of the southern Caspian Sea coastline and coarse grain beaches can be observed in some segments. These

coasts were affected by the Caspian Sea level rise in accordance with their offshore and onshore slopes (Lahijani et al., 2007).

Fig. 4 illustrates the formation of southern Caspian Sea coasts under conditions of rising sea level. The variety of behaviours is due to the differences between offshore and shore gradients (Lahijani, 2009, Pers. Comm.).

Studies related to the sea level rise conducted on the southern coasts of the Caspian Sea are limited and there is a gap in the information available for this area. Although Fig. 4 is a schematic representation of the behaviours prevailing on some coasts it is not sufficient for a coastline of 700 km in length which has a wide variety of features.

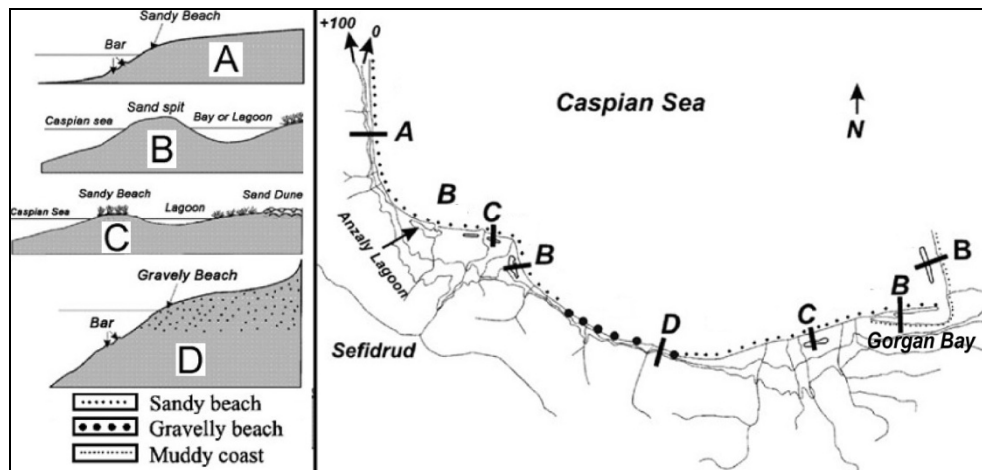


Figure 4. Southern Caspian Sea coasts' behaviour in response to sea level rise (After Lahijani et al., 2007).

## 5. METHODOLOGY

The goal of this research is to investigate the effects of the Caspian Sea water level variations on the Iranian Coast. Factors determining the coastal response to sea level changes include nearshore gradient, sediment supply, wave regime, and sea level rate (Roy et al. 1994), together with shore slope are discussed for the southern Caspian Sea coasts. Response of the southern coast to the water level variations is discussed.

The flowchart illustrated in Fig. 5 shows the process applied in this research in four main steps: the first, the second, and the third field surveys together with the final data analysis. Factors affecting the Caspian Sea coasts were identified by reviewing the literature and background of the subject. On the basis of that knowledge, the first field survey was conducted.

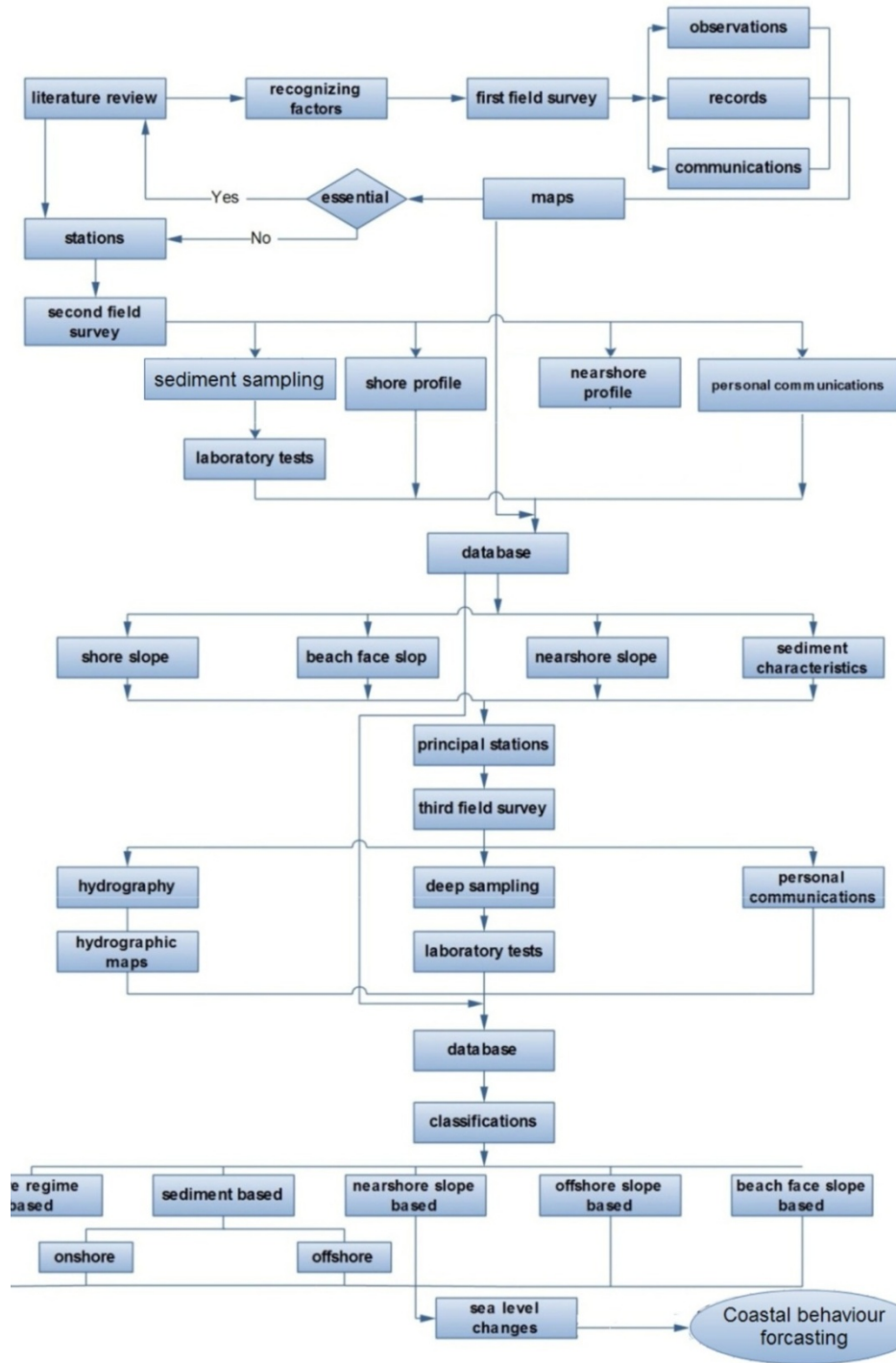


Figure 5. Applied process to examine the impacts of the Caspian Sea level changes on Iran's Caspian Sea coast.

The major objective of initial field work was to gather appropriate information about the study area. For this reason, all observations were documented and locations taken. Also, interviews with coastal residents were performed throughout the survey. Information was compared with the available maps. Finally, the stations of the second survey were chosen.

During second survey the information came from nearshore sediment sampling, offshore hydrography, onshore topography, and personal communications, providing a database for the whole coastline consisting of sediment characteristics, beach profiles, and a general view of each segment of the coastline. Beach profiles provide shore slopes, beach face slopes, and nearshore slopes. A suite of laboratory tests on sediment samples yielded a database of the results. On the basis of the field reconnaissance, principal sampling stations of the third survey were chosen.

The third survey aimed to evaluate deep sediment characteristics of the southern Caspian Sea coast. At this stage hydrographic profiles were surveyed from the shoreline to a depth of 10 m. These profiles were compared with the available hydrographic maps and a set of laboratory tests were conducted on the sediments sampled by divers along profiles at specific depths. The results emerging from this step along with the information obtained from the previous stages created a comprehensive database.

In the final stage, data was analyzed. Several classifications were developed based on wave regime, shore slope, beach face slope, nearshore slope, offshore slope, and sediment characteristics. Finally, the effect of Caspian Sea level changes on Iran's Caspian Sea coasts was evaluated for use in forecasting the behaviour of these coasts in response to future sea level changes.

## **6. THE FIRST SURVEY**

Since field observations play an important role in comprehending the problem, it was decided to study all of the available information, morphological, hydrographic and topographic maps on the scale of 1/100000. These pieces of information were provided by the Iranian Caspian Sea National Research Centre, Iran's National Cartographic Centre, the Geological Survey of Iran, and the Iranian National Institute for Oceanography.

With regard to Fig. 6, the northern part of Iran, where the Southern Caspian Sea coast lies, is divided into three provinces; Guilan, Mazandaran, and Golestan. Guilan province extends from Astara, northeast of Iran where it has a common border with Azerbaijan, to Ramsar, which marks Mazandaran province's border.

Guilan is home to cities such as, Astara and Talesh in the west, Anzali, Dastak and Kiashahr in the centre, and Kelachay in the east.



Figure 6. Three of Iran's provinces bordering the Caspian Sea, 1: Azerbaijan; 2: Astara; 3: Talesh; 4: Anzali; 5: Kiashahr; 6: Dastak; 7: Kelachay; 8: Ramsar; 9: Nashtarood; 10: Noor; 11: Babolsar; 12: Gorgan; 13: Bandar Torkaman; 14: Gorganrood; 15: Gomishan.

Mazandaran province is bounded by Ramsar in the west and to the east it shares its border with Golestan province. The western coasts of Mazandaran are home to cities such as Nashtarood and Ramsar, while Noor is situated in the centre; Eastern Mazandaran is famous for cities such as Babolsar.

Golestan province, the most important city of which is Gorgan, lies on the south eastern coast of the Caspian Sea; its Bandar Torkaman, Gorganrood and Gomishan coasts are amongst those which are important to this study.

The reason why the northern regions of Iran have been described is that the rest of this study and the classifications of coasts use these proper names. Moreover, most of the stations selected in this research are introduced by the names of the cities in which they are situated.

This field survey began in Astara in the west. In almost every region, where even the slightest possibility of access to the coast existed, a survey was carried out. All the observations were documented, and the coordinates of the spots which seemed to be important in later stages were recorded by a hand GPS. For

consequent stages of research, some pictures were taken, while other places where mere pictures could not explain the overall situation were filmed.

Communications with local people were important and helpful in understanding the region. For instance, locals, especially fishermen, had a working knowledge of sandy bars on the nearshore bottom. This survey began on 1<sup>st</sup> May 2009 and finished on 11<sup>th</sup> May 2009 in Gomishan on the east of Iran's northern coast. It covered almost all of the 700 km length of the southern coast of the Caspian Sea. The following are the results of the observations:

1. The morphological phenomena mentioned in section 8.2 are rarely seen all together in one region;
2. Shore sediments and nearshore sediments vary along the coast based on their type, and where the overall width of the coast (the distance between mountain and sea) lessens, the sediments grow coarser.
3. Shore slope varies from place to place;
4. In some parts, the beach face slope is different from the general beach face slope observed along these coasts; that is, the coarser the sediments around the shoreline, the steeper the beach face slope;
5. With attention to the way onshore bars have been formed, one can identify the dominant direction of the sediment transport in some regions;
6. Waves reach the coast at an angle to a line perpendicular to the coastline. This angle varies at different points, lessening as one moves towards the central areas of the coastline;
7. Observations on landforms from sea to mountain, as well as the information obtained from coastal residents about offshore slope, along with previous information obtained from hydrographical and topographic maps, show that both the offshore slope and shore slope are changing along the coast, and these two slopes are substantially different in most regions.

During this survey, the overall morphology of the region was evaluated, and the most outstanding tectonic phenomenon of the region is the Alborz mountain range, by which the whole length of Iran's northern coast is southerly bounded (see Chapter 5, section 5). Also, on the western coastline the Talesh mountain range is oriented in a south-north direction. The distance of these mountain ranges from the sea in different areas of the coastline determines the width of the shore. At some points, the shore width is very narrow, nearly 1 km (for example western Mazandaran, around Ramsar), while in other places such as the eastern parts it exceeds 60 km.

Shore width is one of the factors determining the shore slope, and therefore, it should be paid an appropriate level of attention in this study. In some regions great rivers (for example the Sefid-Rud in central Guilan) which flow into the Caspian Sea expand the shore width. More than 50 rivers flow into the Caspian

Sea from the south, the sediments of which have affected the morphology of the shore and in some cases posed problems for the locals. At a certain point in Kelachay, the local fishermen talked about an obstacle at a depth of around 2.5 m that would tear their fishing nets. Later, in the third field survey, this problem was investigated. On this shore, fishermen would cast their fishing nets in 3–5 m depths of water and after a specified time would drag them out with tractors to gather in the fish. By diving, it was proved that this was a very thin, locally created layer of cohesive clay, probably formed by sediments transported by several small rivers running close to each other. While being dragged along the seabed, the fishing nets must have been torn by this layer.

Onshore sandy bars are mostly seen at the coast at Guilan and eastern Mazandaran, while nearshore sandy bars are formed in most regions, except Golestan (Pers. Comm. with local people, 2009). Small and relatively big lagoons can be seen in eastern Mazandaran and central Guilan. Coastal sediments are mainly sand, except for at the western Mazandaran coast in some segments where gravelly beaches can be seen, and on the Golestan coast where coastal sediments are mostly clay.

After obtaining a general view of the region, it was necessary to match the acquired information with the available maps and studies previously conducted on similar coasts, so that the methodology could be refined.

## **7. THE SECOND SURVEY**

This survey was conducted in order to acquire the information necessary for evaluating Iran's coast. Based on the first survey and supplementary studies, 24 stations were selected along the coast. In Fig. 7 the locations of these stations have been specified. This field work started on 4<sup>th</sup> June 2009 in Astara in the west and finished on 15<sup>th</sup> June 2009 on the Gorganrood coast. During this survey foreshore profiles were mapped, beach sediments were sampled, and observations of shore features were documented. Past information about the Caspian Sea level changes and impacts on coastal geomorphology were collected by personal communications with southern Caspian Sea coast residents.



Figure 7. Twenty-four stations selected during the second survey, 1: Astara; 2: Landvil; 3: Talesh; 4: Parrehsar(1); 5: Parrehsar(2); 6: Kapourchal; 7: Anzali (Bashman); 8: Golshan(1); 9: Golshan(2); 10: Golshan(3); 11: Kiashahr(1); 12: Kiashahr(2); 13: Kiashahr (3); 14: Dastak; 15: Kelachay; 16: Ramsar; 17: Nashtarood; 18: Chalus; 19: Noshahr; 20: Noor; 21: Mahmood Abad; 22: Babolsar; 23: Larim; 24: Gorganrood.

Sediments were sampled along profiles at backshore and surf zone locations in each station. In this research no undisturbed samples were required because the main goal was to determine the grading of the sediments. Cross shore profiles were surveyed within a distance of 150–300 m from the shoreline, dependent on shore slope and landforms. Also, the nearshore profile up to a depth of 1.5 m was mapped by wading.

Selecting 24 stations along 700 km of coastline helped the researchers to gather more complete information about the coast. The high number of selected stations and prolonged timeframe of the whole operation brought about some problems. For example, by taking sediment samples in each station, and each sample weighing about 1 kg, at the end of the operation about 70 kg of these samples was being transported. In some places, access to the shore was problematic, as some parts of the southern coast of the Caspian Sea are owned by private companies or governmental institutes. In some other places, vehicles could not access the points which were considered important for this research, so the equipment had to be carried by survey personnel (e.g., estuary of the Sefirud River near Kiashahr).

The selected station locations were representative of the general situation. A series of laboratory experiments were carried out, as described in the following sections. Finally, comprehensive information about sediments, shore slope, nearshore slope, and beach face slope was acquired. Only information about deep



sediments and overall slope of the seabed was missing. It was decided that in the next survey the hydrography of the seabed should also be carried out.

## **8. THE THIRD SURVEY**

Given that information about the shore and nearshore shallow depths had been acquired, it seemed that with some information about great depths offshore, the information necessary for conducting this research would be complete. On that basis the third survey was planned, the aim of which was to sample sea bottom sediments up to a depth of 10 m and to acquire information concerning the hydrography. For the following reasons, this task was in some respects more difficult than the previous two:

1. The need for boats at specified stations along 700 km of the coast;
2. The need to dive to a depth of up to 10 m;
3. Essential need for the sea to be calm both for diving and for hydrography;
4. The need to obtain required permits for diving and offshore hydrography from local authorities;
5. Identification of more suitable stations which, although fewer in number, would be representative of the whole region;
6. The air capsules needed to be filled with compressed air at each station because the divers were using the air not only for breathing but also to fill their specialist diving suits to help them rise to the surface after sampling.

After reviewing previous data and studies conducted by Iran's Caspian Sea National Research Centre and the Iranian National Institute for Oceanography, eight principal sampling stations were chosen (Fig. 8). The required permits were obtained from local authorities, and two divers were hired for sampling operations. After the climatic status of the two provinces of Mazandaran and Guilan as forecast by weather forecasting centre was reviewed, the 20<sup>th</sup> December 2010 was chosen for the beginning of this survey.

Locals provided useful information about boats for hire at the stations or nearby.

In each station, sediments were sampled by divers along profiles at right angles to the coast at five depths (2, 4, 6, 8, and 10 m). Hydrographic profiles were surveyed by sounding up to a depth of 10 m.

After five days five stations (Astara, Anzali, Dastak, Kelachay, and Nashtarood) had been surveyed. The survey team arrived at Chalus, a city near to Noor which was the sixth station. At this stage a typhoon began to blow and work

stopped and started again after the storm. The survey finished at the last station, on the Gorganrood coast. On this coast, sediments were sampled only at depths of



Figure 8. Principal stations, 1: Astara; 2: Anzali; 3: Dastak; 4: Kelachay; 5: Nashtarood; 6: Noor; 7: Babolsar; 8: Gorganrood.

2 and 4 m. The beach profile was also surveyed to a depth of 4 m because of the very gentle slope of the shore and offshore. To reach a depth of 10 m in this area, a distance of at least 30 km must be navigated (according to the available hydrographic maps) which was not possible because of the lack of available facilities. The sediment samples were carried to a laboratory for testing. Samples were washed with fresh water to remove the salts. Since some sediment samples had a portion of very fine grained particles, the first experiment damaged one sample by removing the finer particles, so this approach was abandoned. Because the Caspian Sea salinity is not as great as that of the oceans, existing salts should not have a serious effect on the result. With the information acquired from this field survey, the required research database was completed.

## 9. THE COAST CATEGORIZATION

Based on the observations, measurements, and information obtained from reviewing the available maps the southern Caspian Sea coast was divided into 5 distinct areas (Fig. 9):

1. West of Guilan Province, from Astara to around Anzali (West Guilan);
2. From Anzali to around Kelachay (Central Guilan);

3. Eastern Guilan and western Mazandaran have common features and were merged to create a zone known as West Mazandaran. Thus, West Mazandaran includes areas from around Kelachay to Noor;
4. From Noor to Gorgan Bay a wide coast can be seen (East Mazandaran);
5. Eastern coasts situated in Golestan Province (Golestan).

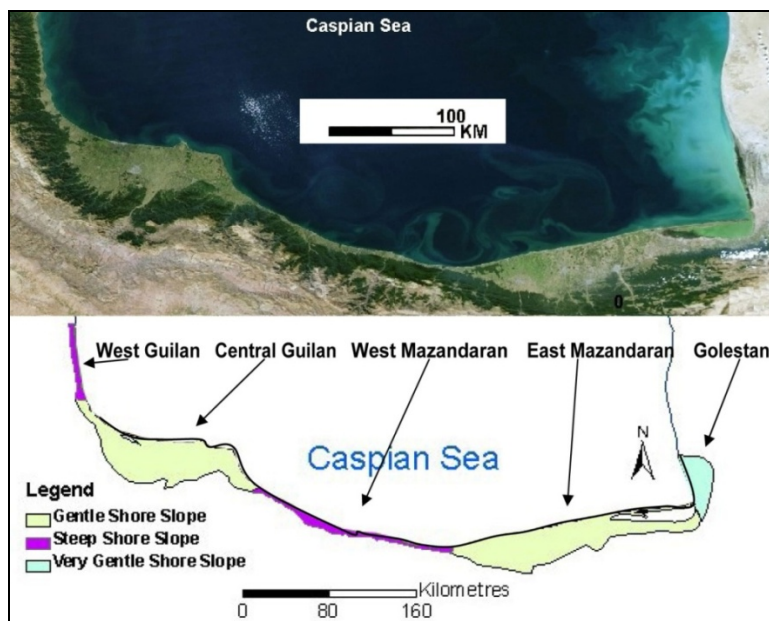


Figure 9. Iran's Caspian Sea coast classification into five areas based on shore slope. Correlation between shore width and shore slope (Data from observations, measurements, and available maps provided by the Geological Survey of Iran, and the Iranian National Institute for Oceanography).

Nearshore gradient, sediment supply, wave regime, and sea level change rate introduced by Roy *et al.* (1994), together with shore slope factors are discussed for these coasts.

## 10. SHORE SLOPE

The database of information obtained from the three surveys and available maps shows that Iran's Caspian Sea Coast can be subdivided into three groups of areas on the basis of the shore gradient (tangent of the shore slope angle):

- a) Areas with a steep gradient (0.01 to 0.07) including West Guilan and West Mazandaran,
- b) Areas with a gentle gradient (0.003 to 0.009) including Central Guilan and East Mazandaran,

- c) Areas with a very gentle gradient (less than 0.001) which can be observed on the Golestan coasts.

Fig. 9 shows a narrow coastline in the western shoreline. Due to a short distance between the mountains and the Caspian Sea in the West Guilan, the shore slope in this zone is steep. In contrast, gently sloping coasts mark Central Guilan. The steep slope of the coast of West Guilan can be observed in West Mazandaran, reaching 1 km at some points. While a gently sloping coast can be found in East Mazandaran, in some parts the shore width exceeds 60 km; Golestan is marked by its very gently sloping coasts. Fig. 9 shows a classification of coastal areas according to their slopes. This figure was produced by combining two maps to show the relation between the location of the mountains, shore width and shore slope. It is believed that the shore slope plays an important role in determining the coastal behaviour in response to sea level changes, a factor rarely taken into consideration in other published studies.

## 11. NEARSHORE BOTTOM SLOPE

Kaplin (1989) suggested that nearshore bottom slope is the factor which most substantially affects coastal behaviour in response to sea level rise. Later, this idea was confirmed by other researchers such as Ignatov *et al.* (1993), Roy *et al.* (1994), Kaplin and Selivanov (1995), and Kroonenberg *et al.* (2000). Nearshore bottom slope determines not only the location of the wave breaking zone and the nature of the breaking process, but the patterns of coastal evolution (Bauch *et al.*, 2005).

Considering Fig. 10 sediment movements are affected by nearshore slope. It shows that under sea level rise, a passive inundation occurs on very gently sloping coasts (a). On coasts with a gentle nearshore slope the dominant direction of sediment transport is landward (b and c), while on the steeper coasts sediments tend to move seaward (d and e).

Kaplin and Selivanov (1995) suggested four patterns for natural evolution of the Caspian Sea coasts under conditions of rising sea level (Fig. 11). Their study revealed that a passive shoreline retreat was marked by a very gently sloping coast (tangent nearshore slope  $(\alpha) < 0.0005$ ) as sea levels rose. On the relatively steep coasts ( $\tan \alpha \cong 0.0005$  to  $0.005$ ), however, depositional submarine bodies (sandy bars) moved landward. Coasts with a steeper nearshore zone ( $\tan \alpha \cong 0.005$  to  $0.01$ ) showed another type of response. On these coasts, lagoons were formed as a result of both the landward movement of the beach ridge and the rising groundwater table, while on the very steep coasts

( $\tan \alpha > 0.01$ ) the dominant direction of the sediment movement was seaward, causing the beach face to erode.

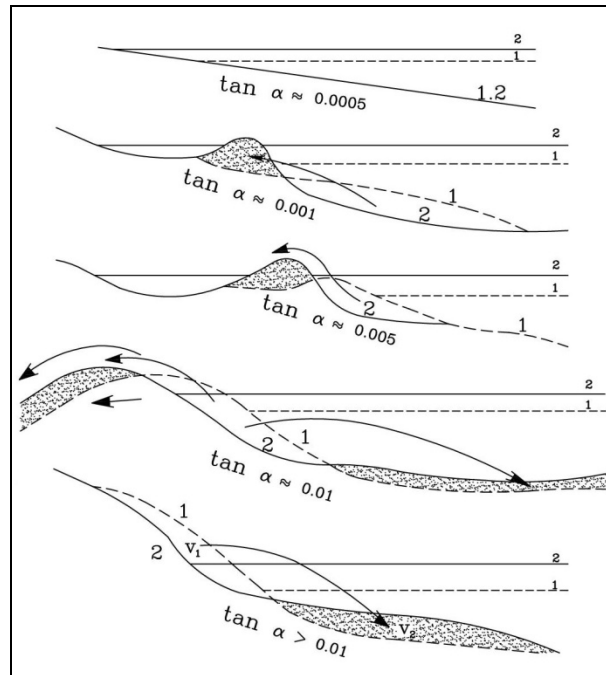
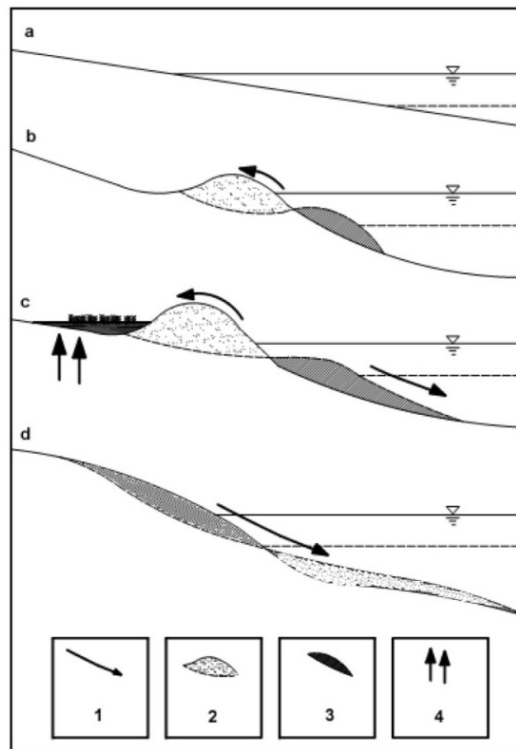


Figure 10. The dominant direction of sediment transport determined by nearshore bottom slope when the sea level rises from the dotted line to the solid line (1 to 2). Dashed areas indicate deposited parts and arrows show the dominant direction of sediment movement (Redrawn after Bauch et al., 2005).

Iran's Caspian Sea displayed specific behaviours, mostly due to the considerable differences between shore slope and nearshore slope on these coasts. In west Guilan around Astara, based on Fig. 11, onshore depositional bodies and lagoons are expected due to the gentle slope of the nearshore zone ( $\tan \alpha \approx 0.001$  to  $0.005$ , based on field data) but during three field surveys, mostly erosional scarps were observed because of the steep slope of the shore.

Iran's Caspian Sea coast can be divided into three areas based on the nearshore slope. Fig. 12 shows the classification of the southern Caspian Sea coasts according to their nearshore slope. A gently sloping nearshore zone marks West Guilan. Coasts with a steep nearshore slope stretched along Central Guilan, West Mazandaran, and East Mazandaran. Low-lying lands of the Golestan coasts are



*Figure 11.* Different types of coastal response to the Caspian Sea level rise, a: passive shoreline retreat on very gentle coasts ( $\tan \alpha < 0.0005$ ); b: landward movement of sediments and sandy bars on relatively steep coasts ( $\tan \alpha \cong 0.0005$  to  $0.005$ ); c: formation of barrier-lagoon system on the steeper coasts ( $\tan \alpha \cong 0.005$  to  $0.01$ ); d: seaward movement of sediments on very steep coasts ( $\tan \alpha > 0.01$ ); 1: dominant direction of the sediment movement; 2: eroding parts; 3: depositional parts; 4: groundwater table rise (modified after Kaplin and Selivanov, 1995).

marked by very gentle nearshore slopes. Fig. 12 shows an obvious difference between the nearshore slope and shore slope throughout Iran's Caspian Sea coastline. Based on this figure the areas defined in section 9 can be characterized as follows:

- a) West Guilan: gentle nearshore slope (tangent slope  $\sim 0.001$  to  $0.005$ ) and steep shore slope;
- b) Central Guilan and East Mazandran: steep nearshore slope (tangent slope  $\sim 0.005$  to  $0.009$ ) and gentle shore slope;
- c) West Mazandaran: steep nearshore slope (tangent slope angle  $\sim 0.008$  to  $0.02$ ) and steep shore slope; and
- d) Golestan: very gentle nearshore slope (tangent slope less than  $\sim 0.0009$ ) and very gentle shore slope.

Fig. 13 shows a classification based on three zones of offshore gradients. Coasts with a gentle offshore gradient are exemplified by West Guilan, where the point at which water depth reaches 100 m is approximately 20-40 km from the shore. This distance decreases to around 6-13 km in Central Guilan, West Mazandaran, and East Mazandaran which have steep offshore gradients, and increases dramatically to around 65-75 km in Golestan which is marked by very gentle offshore gradients. Figs. 12 and 13 show that offshore gradient in each region governs nearshore gradient.

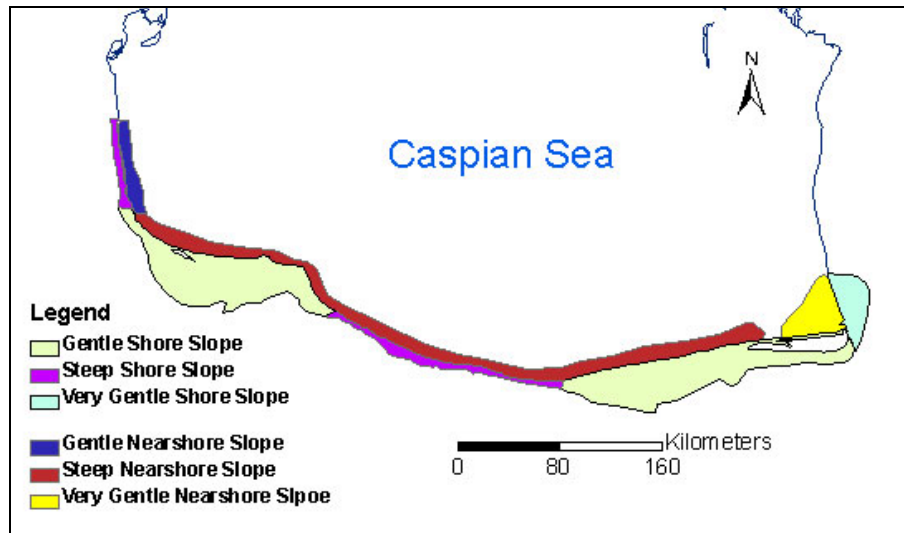


Figure 12. Coastal classification based on nearshore bottom slope, the width of the nearshore zone is not drawn to scale (data from field surveys and available maps).

## 12. WAVE REGIME AND CURRENTS

Waves and currents are driving forces behind many of the coastal processes by which coastal areas are formed. These energy sources are important parameters in the Caspian Sea which influence the morphology of its coasts. The relief of the Caspian Sea bottom isolates three sub-basins from each other which may be one of the causes of water circulation. Rivers feeding the sea are another cause among which the Volga has the most important role because of its considerable discharge (Fig. 14).



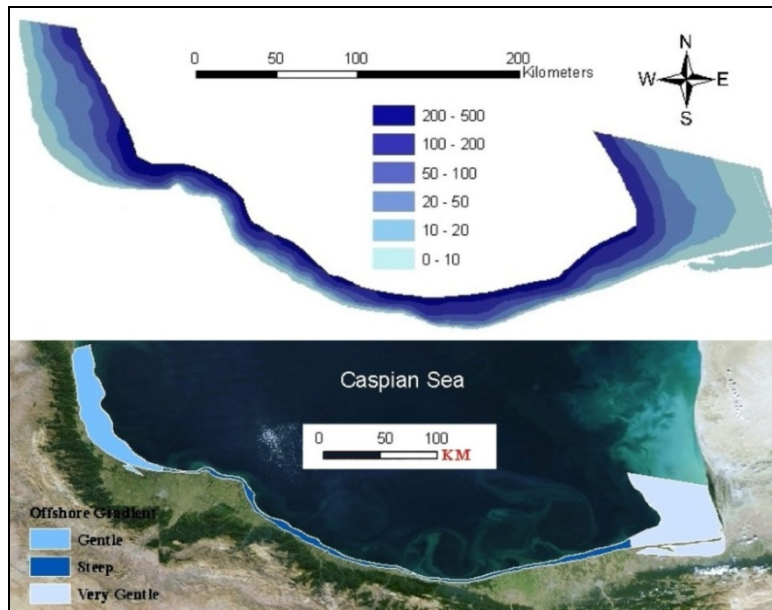


Figure 13. Caspian Sea bathymetry (data from Iran's Caspian Sea National Research Centre) (top). Coastal classification based on offshore gradient along Iran's Caspian Sea coast (bottom).

The North basin is marked by low energy waves and the South basin is characterized by moderate waves. In the Middle Caspian basin however waves have higher energy. Generally, the southern Caspian Sea coasts are exposed to waves which come from the north, northeast and the northwest. The waves coming from the north and northeast reach the western part of the coastline, namely West Guilan, Central Guilan, and West Mazandaran, while the waves reaching the eastern part including East Mazandaran and Golestan come from the North and Northwest (Lahijani *et al.*, 2007). As a result of these waves longshore currents can be observed in a North-South direction along the western and eastern coasts of the south basin and along Iran's Caspian Sea coast a prevailing eastward longshore current flows, the effects of which can be observed in the formation of Gorgan Bay (Fig. 4 and 14).

The southern Caspian Sea coast is mostly dominated by spilling breakers especially in Central Guilan, West Mazandaran, and East Mazandaran. In Golestan the closure depth point is far from the shore, as is the wave breaking point, due to the low beach gradient. As a result, the waves are prevented from approaching the shoreline and do not have a significant impact on the coasts. In West Guilan, nearshore zone is steeper than that of Golestan and waves lose a portion of their energy before reaching the shore, while waves are breaking close to the shore in the other segments of the southern Caspian Sea coastline as a result of the steep gradient of the nearshore zone (Fig. 12).



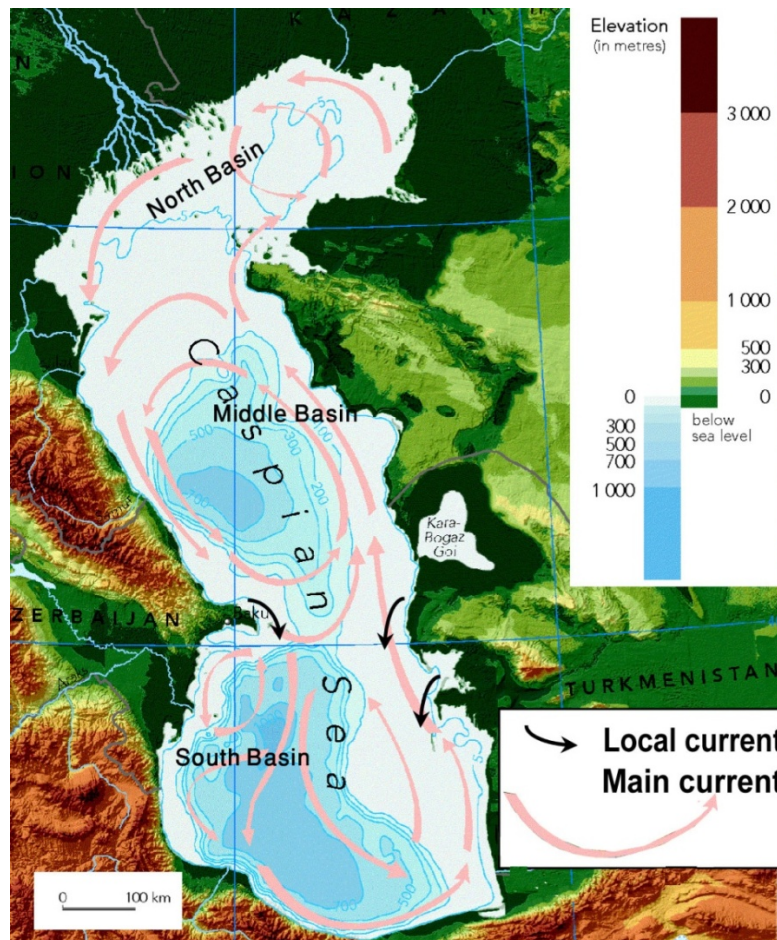


Figure 14. Caspian Sea basins including bathymetry, relief of the surrounding areas, and currents. Local currents are interpreted from headlands (After European Environment Agency).

### 13. SEDIMENT CHARACTERISTICS OF IRAN'S CASPIAN SEA COAST

A necessary part of any coastal investigation is the analysis of sediments sampled from both the shore and offshore. This analysis helps the researchers not only to forecast the future movements and coastal evolution but also to interpret past processes. For this reason all the sediment samples taken from the shore and offshore during the surveys were carried to a laboratory where sieving tests were performed (Guilan University for the second survey's samples and Azad University of Zanzan for the third survey's samples). Sieve analyses were performed in accordance with ASTM C136.

Generally Iran's Caspian Sea coast can be classified into three areas based on onshore sediments:

1. Sandy beaches: West Guilan, Central Guilan, and East Mazandaran;
2. Gravelly beaches: West Mazandaran (in some segments; not the whole coastline); and
3. Muddy beaches: Golestan.

Nearshore sediment is mostly sand throughout the Caspian Sea coast of Iran except that of Golestan which is clay and silt dominated. Also, in some segments of West Mazandaran gravelly particles are seen even at depths of up to 4 m. Moreover, clay and silt particles can be observed at depths along the profiles. In West Guilan clay and silt are observed at depths of over 2 m with the percentage of silt and clay along the profile of the first station of the third survey (Astara) being 38%, 36%, 40%, 25%, and 15% at depths of 10, 8, 6, 4, and 2 m, respectively. In the other stations the presence of silt and clay along the profiles surveyed during the third period of field work were as follows:

- Anzali (Central Guilan): after a depth of 6m (around 2.5% at 6 m, 13% at 8 m, and 18% at 10 m);
- Dastak (Central Guilan): after a depth of 4 m (around 5% at 4 m, increasing seaward);
- Kelachay (Central Guilan): after a depth of 2 m (around 3% at 2 m, 11% for 4 m, and 15% for 6 m, increasing seaward);
- Nashtarood (West Mazandaran): after a depth of 6 m (around 9% at 6 m, increasing seaward);
- Noor (West Mazandaran): no clay and silt observed until a depth of 10 m;
- Babolsar (East Mazandaran): after a depth of 6 m (around 25% at 6 m, increasing seaward)

Generally, silt and clay along the Caspian Sea coast of Iran can be observed from a depth of 2 m seaward in West Guilan. In Central Guilan and East Mazandaran the depth at which clay and silt exists is 6 m while for West Mazandarn usually there is no clay and silt in the samples taken from depths up to 10 m. In Golestan both shore and nearshore sediments are dominated by clay and silt.

#### **14. ANALYSIS OF THE IRANIAN CASPIAN SEA COAST AND FUTURE FORECASTING**

This study classifies the southern Caspian Sea coast into four groups - West Guilan, Central Guilan-East Mazandaran, West Mazandaran, and Golestan - each

of which will be discussed here to characterize its nature and to forecast its evolution under conditions of probable future sea level change, as discussed in previous sections.

West Guilan: generally this coastal zone has a steep shore slope (tangent slope angle  $\sim 0.01$  to  $0.05$ ) and gentle nearshore slope (tangent slope angle  $\sim 0.001$  to  $0.005$ ) which follows the gentle offshore gradient in this area (Fig. 13). Based on Fig. 11, this zone falls into group b of Kaplin and Selivanov's (1995) classification but the steep slope of the shore forms erosional scarps on the beach face. It is suggested that, given future sea level rise in this zone, erosional scarps and submarine sandy bars will be formed, specifically from Astará to around Talesh, and in some areas, specifically from Talesh to Anzali, small lagoon-barrier systems will be created around the mouths of the small rivers entering the Caspian Sea where the shore slope is becoming relatively lower and coarse grained material is provided by rivers. Under conditions of falling sea level however, the shore would widen and consequently onshore sandy bars would form. No lagoon is expected to form except for a few very small lagoons around the river mouths.

Central Guilan-East Mazandaran: since gently sloping shores (tangent slope angle  $\sim 0.003$  to  $0.009$ ) but steep nearshore slopes (tangent slope angle  $\sim 0.005$  to  $0.009$ ) mark this zone, this group of areas mostly fall into group c of Kaplin and Selivanov's (1995) classification. On shore and submarine sandy bars together with sandy dunes are seen in these areas. As a result of formation and landward movement of barriers, several big lagoons and a notable number of small lagoons were formed during the recent sea level rise. With future rises in sea level these conditions are expected to continue and lagoons may increase in size due to the gentle shore slope of this area and the existence of a wide shore. When the sea level falls, no big lagoons are formed and existing lagoons lose their size (personal communication with East Mazandaran residents). Submarine depositional bars emerge and other bars are formed by storms.

West Mazandaran: having both steep shore and nearshore gradients (tangent shore slope angle  $\sim 0.01$  to  $0.07$  and tangent nearshore slope angle  $\sim 0.008$  to  $0.02$ ) this coastal zone mostly falls into group d of Kaplin and Selivanov's (1995) classification and, in a few segments, into group c. Hence, in this zone the steep gradient of the nearshore zone prevents the sediment from moving shoreward and onshore bars are very rare (observations agree with this). As a result of seaward movements of the sediments multiple bars are formed on the nearshore bottom. Given a future rise in sea level more sediments can be expected to move seaward and under an accelerated sea level fall depositional submarine bars may emerge without losing their size.

Golestan: in this zone both the nearshore and shore slopes are very gentle (tangent nearshore slope angle less than  $\sim 0.0009$  and tangent shore slope angle less than  $\sim 0.001$ ) and a passive shoreline regression and transgression occurs under sea level changes.

## 15. CONCLUSION

Recent Caspian Sea level changes make this sea a unique natural laboratory for studies related to coastal response patterns. This research examined the Iranian coast of the Caspian Sea to introduce its behaviour in response to sea level changes which can be applied to predict future evolutions. All available maps were reviewed and three field surveys were performed: the first survey provided useful information and gave a general insight into the study area; the second survey was aimed at nearshore sediment sampling, nearshore hydrography, and shore topography; and the third survey evaluated deep sediment characteristics and provided hydrographic profiles surveyed from the shoreline to a depth of 10 m. A database was created including information about: shore slopes, nearshore bottom slopes, sediment characteristics, and longshore current regime. This research classified the southern Caspian Sea coast into four categories with respect to their response to sea level change: West Guilan with gentle nearshore slope and steep shore slope; Central Guilan and East Mazandaran with steep nearshore slope and gentle shore slope; West Mazandaran with steep nearshore slope and steep shore slope; and Golestan with very gentle nearshore slope and very gentle shore slope.

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