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South Caspian River Mouth Configuration Under Human Impact and Sea level Fluctuations

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Abstract
Rivers that flow from the Iranian coast to the Caspian Sea encompass 135,000 km^2 of that catchment's basin and supply 40 million ton sediment to the Caspian coast annually. The dynamics of river mouths and deltas are studied using hydrological data of the rivers, air photos, satellite images and geological and geomorphological maps as well as field observations and sediment sampling. Results from this study show that the morphology of the river mouths and deltas are mainly controlled by marine (ware-induced currents and sea level changes) and fluvial processes. Among these factors, sea level and riparian sediment supply have great variability. Analysis of hydrological data revealed that, during the past few decades with increasing human activities, the sediment supply of the rivers reduced from 10 to 40 %. The Caspian sea level has changed over a range of 3 m during instrumental measurements. The rivers are classified into three groups based on the morphology of their mouths and the nature of river/sea dynamics: Type 1 is rivers that enter to the sea through lagoons and lowlands. They have gained an ephemeral nature due to increasing water consumption recently. Type 2 rivers have a normal flow into the Caspian Sea. They are common in steep slope coasts, where they are rarely affected by human activities and sea level changes. On moderately sloping coasts, they are slightly affected by long-shore currents of the sea. Some distributaries of the rivers enter into the sea independently. Some bars and lagoons are developed in the vicinity of the river's mouth, most commonly since the last sea level rise. Type 3 represents the great rivers with a significant sediment supply (Sefidrud River in the West and Gorganrud River in the East), producing deltas and mouth bars. They have high sediment discharge into the sea and are more greatly affected both by human activities and sea level changes.

Keywords: river delta, south Caspian sea, sea level change, delta classification.

مرفولوژی دهانه رودخانه‌های جنوب خزر در شرایط اثر عوامل انسانی و نوسان تراز آب

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چکیده
رودخانه‌هایی که از ساحل ایران به خزر می‌ریزند با مساحت حدود یکصد و سی و پنج هزار کیلومتر مربع، سالانه حدود چهل میلیون تن رسوب وارد خزر می‌کنند. دینامیک دهانه رودخانه‌ها و دلتاها با استفاده از داده‌های آب‌شناختی رودخانه، عکس‌های هوایی، تصاویر ماهواره‌ای، نقشه‌های زمین‌شناختی و ریخت شناختی و همچنین مشاهدات و نمونه‌برداری‌های میدانی مورد مطالعه قرار گرفت. نتایج این مطالعات حاکی است که ریخت-شناسی دهانه رودخانه‌ها و دلتاها عمدتاً به وسیلهٔ فرایندهای دریایی (جریان-های ناشی از موج و نوسان تراز آب) و رودخانه‌ای کنترل می‌شود. در بین این عوامل، تراز آب دریا و فرآوری رسوب رودخانه‌ای دارای تغییرات زیادی است. بررسی داده‌های آب شناختی نشان داد که در چند دههٔ اخیر با افزایش فعالیت‌های انسانی، فرآوری رسوب رودخانه‌ای از ۱۰ تا ۴۰ درصد کاهش یافته است. تراز آب خزر در طی اندازه‌گیری‌های دستگاهی حدود ۳ متر نوسان داشت. بر حسب ویژگی ریخت‌شناسی دهانه رودخانه و دینامیک محیط دریایی و رودخانه‌ای، می‌توان دهانهٔ رودخانه را به سه گروه تقسیم کرد: نوع ۱: رودخانه‌هایی که از طریق سرزمین‌های پست و تالاب-های ساحلی وارد دریا می‌شوند. این رودخانه‌ها با افزایش مصرف آب، به رودخانه‌های فصلی تبدیل شده‌اند. نوع ۲: شامل رودخانه‌هایی با ورودی معمولی به دریا است. این رودخانه‌ها در سواحل پرشیب کمتر توسط عوامل انسانی و تراز آب تأثیر پذیرفته‌اند. در سواحلی با شیب متوسط، دهانه این رودخانه‌ها توسط جریان طولی ساحلی منحرف شده است. در این حالت برخی از شاخه‌های فرعی آن‌ها به طور مستقل وارد دریا می‌شود. بارهای رسوبی و تالاب‌های جانبی در طی افزایش تراز آب در دهه‌های اخیر در دهانه این رودخانه‌ها در سواحل با شیب متوسط توسعه یافته‌اند. نوع ۳: رودخانه‌های بزرگ با فرآوری رسوب زیاد (سفید رود در باختر و گرگانرود در خاور) که ایجاد دلتا و بارهای رسوبی دهانه‌ای کرده‌اند. این رودخانه‌ها درارای آورد رسوبی قابل توجه به دریا هستند و هم از فعالیت-های انسانی و هم از نوسان تراز آب تأثیر پذیرفته‌اند.

کلیدواژه‌ها: دلتای رودخانه‌ای، خزر جنوبی، نوسان تراز آب، طبقه‌بندی دلتاها.

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Introduction

The morphology of transitional depositional systems (especially deltas) depends on both basinal and terrestrial factors, such as sea level changes, wave and wave induced currents, tidal ranges, and sediment supply (Coleman and Wright, 1975; Elliott, 1986; Galloway, 1975). River mouths as a place of sediment input to the basin play a significant role as sink basins and produce a special coastal morphology. These processes involve a variety of interaction between riverine and basinal waters (Wright, 1977). They contribute to delta formation if the sediment supply to the receiving basin is sufficiently large. Delta plains, as the gift of rivers to the basin are important features in coastal region (Saito, 2005) and play important role in human civilization (Wright, 1978).

Morphology of river mouths that enter the Caspian Sea as a closed basin with a maximum 12 cm tidal range (Terziev, 1992) are mainly affected by fluvial and basinal processes. Wave and wave-induced currents, rapid sea level changes and fluvial sediment supply are controlling factors that modify the Caspian river mouth configuration (Azimov *et al*., 1986; Mikhailov, 1997; Voropaev *et al*., 1998b). The north Caspian deltas are developed on a gently sloping near-shore and continental shelf, experiencing a low wave energy condition whereas the western and southern Caspian deltas experience high wave energy on the steeply sloping continental shelf (Azimov *et al*., 1986; Mehdiev, 1966; Voropaev *et al*., 1998a). The Caspian Sea deltas are exposed to a rapid sea level fluctuation in a range 100 times greater than that which occurs in the oceans (Kroonenberg *et al*., 2000). The drainage basin of the Caspian Sea covers an area of 3.5 million Km^2 (Mikhailov, 1997). In recent decades, human activities in the drainage basin of the Caspian Sea have changed the natural fluvial regime (Krasnozhon *et al*., 1999; Lahijani and Krasnozhon, 1999; Mikhailov, 1997). The most prominent human impacts were reducing water and sediment discharge at a rate of 10 % and 40 %, respectively. The Caspian Sea now suffers from an annual shortfall of around 40 Km^3 of run off compared to the time when the river flow was not regulated (Zonn, 1996). It accounts for a one meter sea level fall since the 1950s. Dam construction, irrigation, sand and gravel excavation from rivers have reduced river loads to 40 %. This culminates in river mouth erosion and retreat of seaward edge of deltas. Moreover, these changes have caused significant ecological impacts in the river mouths and the Caspian Sea. A sharp decrease in the fish stock of the Caspian Sea during the past few decades can be attributed to a reduction in the fish migration into the river mouth in spawning period (Saiko, 1996)

All 61 rivers that flow from Iranian coast to the Caspian Sea are subject to intensive human activities. A densely populated coastal area (7 million settlements in 15000 Km^2) and distribution of high water consuming crops such as rice and cotton makes the Iranian coast of the Caspian Sea different from other parts of the sea (Lahijani, 2004). The human regulation of the rivers has affected not only the total mass of the water and sediment discharge but also its distribution throughout the year (Voropaev *et al*., 1998b). Under the natural conditions of the past, spring floods had a slow start and a slow cessation. By contrast, floods occurring nowadays are distributed over the spring and autumn months. All changes in forcing factors to the river months, both human-induced and natural factors, contribute to the change and adjustment of the river entrance to the Caspian Sea. Iran's southern Caspian coast receives 61 rivers of which only two of them (the Sefidrud and Gorganrud Rivers) have built deltas in the Caspian Sea. The small rivers entering from the southern Caspian coast make simple river mouths that are sensitive to forced factors.

In spite of a huge literature on the northern and western Caspian coast deltas, the southern Caspian rivers and deltas are poorly understood. This paper aims at introducing southern Caspian river mouth morphology based on natural processes and the impact of human activities. The major attention will be paid to the Sefidrud River delta, since it is the greatest river in the south Caspian coast.

The Caspian Sea and its Catchment Area

The Caspian Sea is a semi-eclipse basin oriented in a N-S direction with a length of about 1,200 km and width of about 400 km. The sea surface (at a 28 m height) is around 360,000 km^2 and the water volume exceeds 78,000 km^3 (Nikolaeva, 1971). On the basis of the sea floor morphology, the Caspian Sea is divided into three sub-basins: northern, middle and southern with the average, maximum depth increasing from North to South (Voropaev, 1986).

The Caspian Sea catchment basin covers an area of 3.5 km^2, which is mainly located in the littoral states of Iran, Turkmenistan, Kazakhstan, Russia and Azerbaijan, and with small parts in Turkey, Armenia and Georgia (Mikhailov, 1997; Voropaev, 1986) (Figure 1). The northern part of the basin is located in high latitude forests, middle Volga steppe and Pre-Caspian deserts. The western and southern parts of the basin are situated in the high mountain ranges of the Caucusus and Alborz, respectively. The Copet-Daq Mountains cover the southeastern part and whole of the eastern part comprises a wide area of deserts (Voropaev, 1986). The Caspian drainage basin in Iran covers an area of 185,000 km^2, which encompasses the whole of the northern part of Iran. The northwestern and northeastern rivers of Iran flow into the sea through Azerbaijan and Turkmenistan, respectively (Afshin, 1993; Lahijani, 1997). The rivers that flow to the Caspian Sea through the Iranian coast have a drainage basin of 135,000 km^2, most of which is located on the northern flank of the Alborz Mountain range. The Sefidrud as the greatest river of the Iranian coast drains various parts of the Zagros and Alborz mountain ranges. Gorganrud on the East coast is another river that cut through Alborz and drains the Copet-Daq mountain range. Before arriving at the sea, the rivers pass through a rugged topography with elevations of 100 m up to 4,000 m. The catchment area is characterized by a wide variety of rocks ranging in age from the Precambrian to the Quaternary eras (Nowroozi, 1971; Stocklin, 1974, 1977; Sussli, 1976).

Around 130 rivers flow into the Caspian Sea through the northern, southern and western coasts (Terziev, 1992). The eastern coast is characterizes by the lack of fluvial discharge. The northern Caspian rivers drain vast areas of the Russian plain and encompass 90% of the freshwater discharge into the Caspian Sea (Mikhailov, 1997). Western and southern Caspian rivers originate from the steep slopes of the Caucuses and Alborz mountain ranges, respectively. Rivers with a low discharge rate are mainly located on the western and southern coasts where a narrow coastal plain constrained them between the sea and the neighboring mountains (Azimov *et al.*, 1986; Lahijani, 1997).

Caspian basinal factors

After separating from the Black Sea in the Pliocene period (about 5.5 million years ago) (Reynolds *et al.*, 1996), the Caspian Sea has shown different cycles of sea level changes ranging up to 300 m (Rychagov, 1997; Varushchenko *et al.*, 1987). The sea level has rarely been constant throughout time and space. Different processes are found to be responsible for the changes. Instrumental measurements show that the Caspian Sea level has changed around 3m during the past 120 years (Frolov, 2003). The river influx, mainly from the Volga River, and evaporation over the sea surface (Radionov, 1994; Kislav and Surkova, 1998) are mentioned as main causes, but the mechanisms that contribute to such changes have not been clearly understood yet (Mikailov, 1997).

Wave and wave-induced currents are major basinal parameters of the Caspian Sea which affect the coastal morphology (Leontiev *et al.*, 1977; Mikhailov, 1994). Activities of the atmospheric systems over the Caspian basin, sea floor topography and coastline configuration determine the wave regime in the sea (Koshinskii, 1975; Terziev, 1992). The middle, South and North sub-basins are characterized by high, moderate and low wave energy, respectively (Ivanov, 1986) (Figure 1).

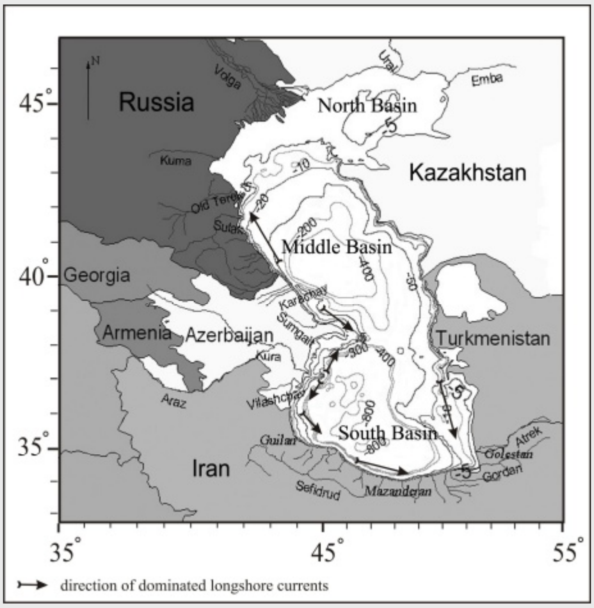


Figure 1- Caspian Basin including bathymetry and major rivers.

In this regard, the South Caspian is divided into western and eastern parts. The waves reaching the western Iranian coast come mainly from the North and Northeast, whereas those of eastern part mainly come from the North and Northwest (Terziev, 1992). The waves produce prevail southward long shore currents on the West and East and eastward currents on the South coast of Iran (Voropaev *et al.*, 1998b; Zenkovich, 1957). In the eastern and western parts of the Iranian coast, the waves approaching land are significantly modified by the sea floor topography, due to the slight topography of the coast. Therefore, in comparison to the central South coast, the western and eastern coasts of Iran are characterized by lower energy (Lahijani, 1997).

Data Gathering

Monthly hydrological data of Iranian rivers have been used for estimating total water and sediment supply to the Caspian Sea (Hydrometeorological Yearbook, 1999). A total of 23 surface samples have been collected from the main river mouths for sedimentological studies. Historical maps, aerial photographs and satellite images, along with previously published information, have all been used to compare river mouth changes.

Results And Discussion

South Caspian Rivers

In the South Caspian Sea, sediments are transported to the coast by 61 rivers which flow from the northern flank of the Alborz, except for two of them. The Sefidrud River in the West and the Gorganrud River on the East coast began their courses from Zagros and Copet-Daq Mountains, respectively. The rivers annually supply about 40 million tons of sediments to the shoreline in total (Voropaev *et al.*, 1998a). A wide variety of igneous, metamorphic and sedimentary rocks cover the catchments area of the rivers. The Sefidrud River starts from metamorphic and igneous rocks in the Zagros mountain range, then passing badland of the Neogene series, cuts the Alborz range and enters the southern Caspian coastal plains. The Gorganrud River passes through sedimentary rocks of the Copet Dag range, mainly composed of carbonates, flowing to the southeastern Caspian coastal plain which consists of Quaternary marine and fluvial unconsolidated deposits.

Most of the Sefidrud Basin has poor vegetation coverage while, cutting the northern slope of the Alborz Mountains, it is characterized by a dense forested area. The similar vegetation covering could be seen in the headwater and mid-basin of the Gorganrud River as well, except that the downstream is located in the arid region. Moderate rivers originate in the northern slopes of the Alborz range. Their headwater is located in a mountainous area with little vegetation covering that gradually changes to a densely forested area, then they pass through the South Caspian coastal plain. The small rivers mainly begin from densely vegetated hills with average an elevation of 200-300 m (Figure 2).

(j): Tajan basin. (k): East Mazanderan basin, main river: Neka. (l): Golestan basin, main river: Gorganrud. (m): Water of north- east Iran flows through Turkmenistan (Atrek River) to the Caspian Sea.

Annual precipitation in the south Caspian coasts varies from 1,500 mm in west to 150 mm in the east. Vegetation, humidity and temperature of the coasts change from subtropical in the west to arid/semiarid in the east (Khaleghizavareh, 2005). Precipitation over the upstream of the Sefidrud and Gorganrud Rivers is about 300 mm and 200 mm, respectively. Precipitation in the coastal plain and forested areas, occurring mostly as rain, is distributed throughout the year. Upstream of the major and minor rivers receive their water as snow that falls during cold season (November to March).

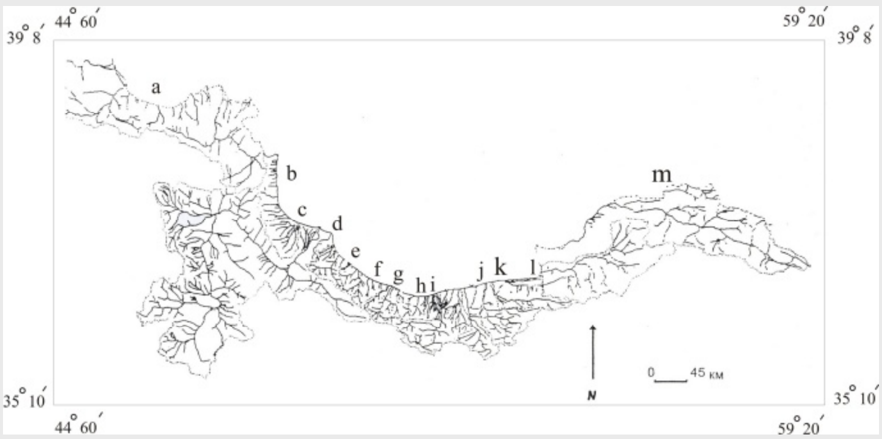


Figure 2-Caspian Catchment basin in Iran.

(a): Water of north-west basin of Iran flows through Azerbaijan territory to the Caspian Sea (Arkas- Kura). (b): West Guilan basin, main river: Karganrud. (c): Anzali Lagoon basin, main river: Pasikhan. (d): Sefidrud Basin.(e): East Guilan basin, main river: Polrud.(f): West Mazanderan basin, main river: Cheshmehkile.(g): Central Mazanderan basin, main river: Chalus. (h): Haraz basin. (i): Talar and Babolrud basin.

Sediment loads of the rivers are significantly controlled by their geological setting, vegetation and the morphology of the catchment area. The smaller rivers have a negligible sediment load. Moderate rivers with a high gradient bottom topography are more common in the central and western parts that are characterized by a coarse-grained bed load. Moderate rivers of the central and eastern coasts supply large amounts of suspension load both due to easily erodable material over the catchments basin (Neka River) and the unconsolidated volcanic ash of Damavand (Haraz River). The mean water and sediment discharge under natural conditions from the rivers of the Iranian coast is around 16 Km^3 and 47 million ton per year (Lahijani and Krasnozhon, 1999). The Sefidrud, as the South Caspian's largest river, contributes to 70 % of the total sediment supply from Iranian coast (Table 1; Figure 3).

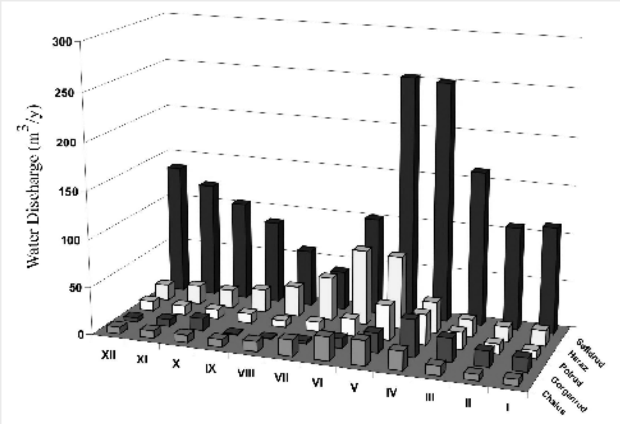


Figure 3- Mean annual water discharge of five rivers: Sefidrud, Haraz, Polrud, Chalus and Gorgunrud.

Table 1. Iranian rivers and their main characteristics.

Name of River	Catchment Area (Km2)	Length of River (Km)	Water discharge (million m3/y)	Sediment discharge (million tons/y)
Acharud	-	16	41	-
Astara	180	36	-	-
Babol	1500	170	489	0.440
Baghu	30	14	2	-
Chalkrud	480	56	51.9	
Chalus	1550	180	401	0.411
Cheshmeh kileh	1450	80	442	0.426
Chubar	-	27	-	-
Galand	320	54	-	-
Garyrud	-	19	32	-
Gorganrud	12600	350	407	3.080
Haraz	4100	185	1072	2.367
Jelvandi	80	20	65	
Kajur	450	54	-	-
Kaliak	90	27	10	-
Kanrud	-	16	-	-
Karganrud	550	70	390	0.300
Kazemrud	120	18	51	-
Kensrud	-	-	-	-
Khashesar	225	60	-	-
Kheirud	220	34	14	-

Table 1. Iranian rivers and their main characteristics.

Name of River	Catchment Area (Km2)	Length of River (Km)	Water discharge (million m3/y)	Sediment discharge (million tons/y)
Khotbesara	-	16	-	-
Lamir1	180	40	85	-
Lamir2	-	27	84	-
Langrud	260	54	313	-
Larim	130	65	13	-
Lavandavil	60	18	52	-
Lisar	-	-	-	-
Luard	-	20	6	-
Masulehrud	280	65	107	-
Mordabrud	60	20	101	-
Namak Ab	-	12	-	-
Nashtarud	200	50	31	-
Natelrud	140	24	-	-
Neka	3000	180	154	0.422
Novrud	390	50	64	-
Nowshar	70	24	28	-
Pasikhan	840	60	444	-
Plangdareh	-	14	-	-
Plangrud	450	70	77	-
Polrud	1650	80	476	1.000
Rostamrud	170	60	10	-
Rudsar	80	28	-	-
Safarud	130	35	66	-
Sardabrud	430	67	44	-
Sarijeh	-	46	-	-
Sefidrud	67000	800	4037	26.000
Seighalan	350	55	227	-
Shafarud	350	55	193	-
Shakhraz	230	54	120	-
Shalmanrud	390	54	222	-
Shanderman	210	60	73	-
Shirabad	-	15	-	-
Siah Ab	1500	80	54	-
Siah Darvishan	350	63	72	-
Siah Darvishan	350	55	227	-
Tajan	4000	192	417	0.377
Talar	2850	150	319	1.115
Tilerud	40	15	-	-
Vazrud	250	65	-	-
Zavar	-	10	-	-
Aras*	$\frac{102000}{38600}$	1070	7900	-
Sari Ghamish *	1100	120	-	-
Atrak**	$\frac{28000}{26900}$	715	123	-

* Part of catchment basin in Iran

** Part of catchment basin out of Iran

Small and Moderate River Mouth Morphology

Small rivers rarely have enough energy to cut through the beach and make a distinct river mouth. They loose their energy in the coastal lowlands, where they form a small scale fan or enter into the coastal lagoons (Figure 4a and 4b). The patterns of small river mouths are mainly controlled by coastal climate and human activities.

The general outlines of the moderate river mouths differ significantly in the coastal area. Moderate rivers that flow through the West coast of Guilan Province and East of Mazanderan Province are modified by strong long shore currents. They shift toward the direction of dominant long shore currents.

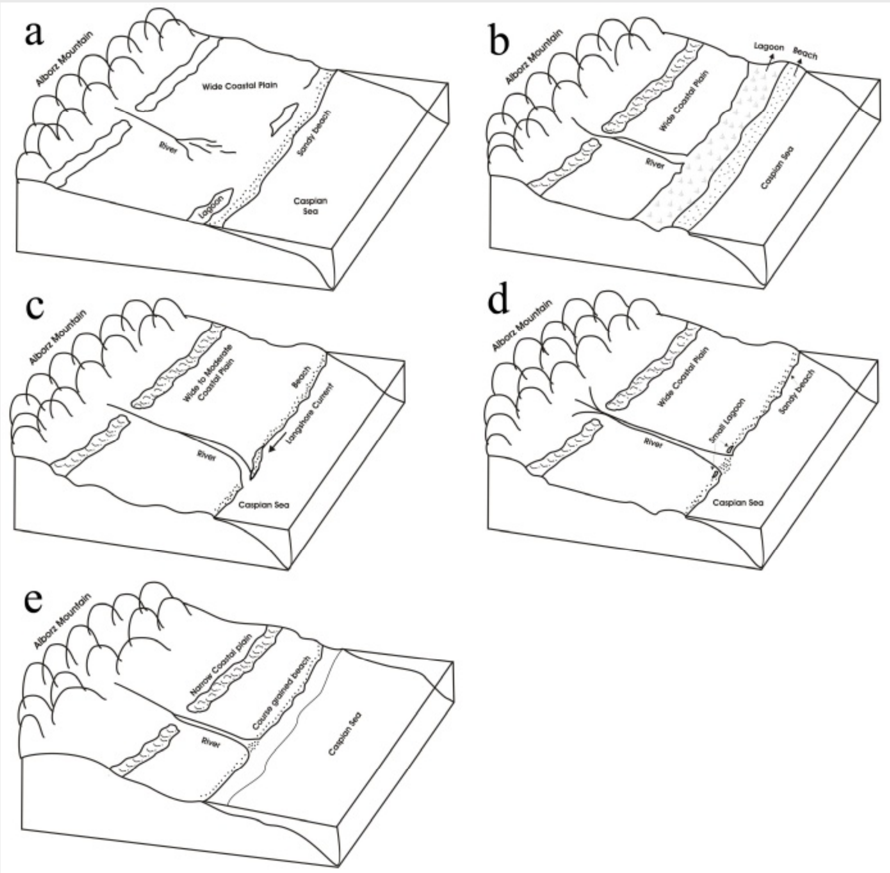


Figure 4. 3-D diagram of river mouth evolution of south Caspian Coast.

(a): Small rivers that disappear in coastal plain.

(b): Small rivers that enter into the coastal lagoons.

(c): Medium rivers that incline to the direction of dominant longshore current.

(d): Medium rivers that have lateral lagoons and mouth bar.

(e): Medium rivers composed of coarse- grained material in the mouth.

Lateral shifting of the channel causes the growth of bars and spits in the eastern side of the river mouth and an increment of the beach in the eastern part (Figure 4c). Moderate rivers with a high discharge that enter into the coast with weaker long shore currents (East Guilan and central Mazanderan Provinces) produce subaqueous mouth bars and lateral lagoons (Figure 4d). In the summer, while riverine discharge decreases, the mouth bars partially play the role of barrier between sea and river. Steep gradient rivers (particularly in west Mazanderan) supply a coarse-grained sediment load into the steep slope near shore area. Strong cross-shore currents remove the sediments and produce wide simple river mouths (6e). Seawater does not enter into the river mouths under natural conditions because of the negligible tidal regime, the presence of shallow river mouth bars in moderately sloping coasts and strong river currents in high gradient rivers. During storm surges which rarely raise water level up to 1 m in the southern Caspian sub-basin, seawater intrusion into the river mouth can occur. Artificial deepening of the Babolrud River mouth for its port navigation causes the free exchange of seawater into river mouth.

Large River Mouth Morphology

The 820 km long Sefidrud River originates in the Zagros Mountains of western Iran at an elevation of around 4,800 m. It flows down to the northeast where it connects to rivers from southern flank of the Alborz Mountains. Then it changes its direction northward and cuts the Alborz Mountains where it is characterized by narrow valley 200-500 m wide. It forms a wide coastal plain in the vicinity of Rasht city. Passing the Alborz range, the Sefidrud receives small rivers flowing from the northern flank of the Alborz Mountains. Some part of the sediment discharge is related to these rivers' activities. The coastal plain is characterized by abundant distributary channels and extensive flood plain, on which local swamps are common. Sediments with marine characteristics are locally observed on the coastal plain, which reflect sea level affects on the plain. The main channel of the river flows into the Caspian Sea near Kiashahr city, where it forms the Sefidrud delta. The main channel of River shows a high sinuosity within its alluvial valley, resulting in numerous abandoned channels. The old Sefidrud River (30 km East of Kiashahr) was the main channel in about 1600 A.D. It was responsible for the development of an ancient delta in Northeast Lahijan (Lahijani *et al.*, 2008). The drainage basin of the Sefidrud River is around 66,000 km^2, which is mostly located in mountainous regions with an arid and semi-arid climate and poor vegetation cover (Hemmati and Fateh, 2004). The catchment basin comprises igneous, metamorphic and sedimentary rocks of poorly consolidated Cenozoic red beds. The climate and geological setting of the Sefidrud River are responsible for its high sediment discharge into the Caspian Sea. The region on which the Sefidrud delta is developed is characterized by continental and nearshore slopes of 0.2 % and 0.5 % respectively. Such characteristics allow northerly and northwesterly waves to produce strong eastward long shore currents on the shoreline. Therefore, the Sefidrud delta deposits are subject to the distribution and reworking by the long shore currents associated with rapid sea level fluctuation. Compared to the other effects in the basin, the wave action in the Sefidrud delta is most significant (Kousari, 1986). High wave energy along the delta lobes results in the development of wave-reworked landforms. Consequently, vast beach ridges and sand dunes with well sorted sands are developed. The long shore current reshapes the delta as an eastward-inclined triangle. Distributions of the land derived sediments by the long shore currents produce linear barrier islands and spits witch enclose broad brackish bays and lagoons. A typical example of this occurs on the old Sefidrud delta where Amircola back barrier-lagoon is formed. The modern barrier-lagoon in the eastern part of Sefidrud has eroded due to the sea level rise since 1979. The Sea level rise has changed the wave and current actions to the higher elevation along the coast. In turn, they have reworked some parts of the older delta plains into a series of beach-barrier complexes, which differ from the barrier lagoons developed through littoral drift (Lahijani *et al.*, 2008). The modern delta lobe covers an area of 10 km^2.

The older lobes distributed in the central Guilan in area around 2000 km^2. During rapid sea level rise e.g. the past 30 years, seawater floods delta plain, where shallow lagoons are formed**.** At the river mouth, broad sandy and silty bars, often barren of vegetation, are formed (Figure 5).

Gorganrud, as a moderate river as far as the water discharge is concerned, enters into the gently sloping near shore area which is characterized by low wave energy. It deposits its sediment load as a triangle into the Caspian Sea (Figure 6).

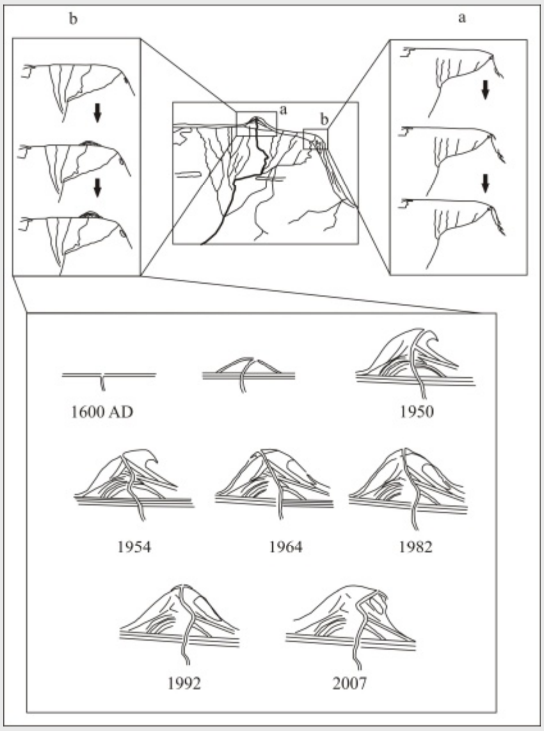


Figure 5. Main evolution stages of Sefidrud Delta.

a) Evolution of old Sefidrud Delta and enclosing Amirkola Lagoon through enlargement of Amirkola Spit.

b) Sefidrud River avulsion and formation of new Sefidrud Delta westward of the old delta (1600 AD).

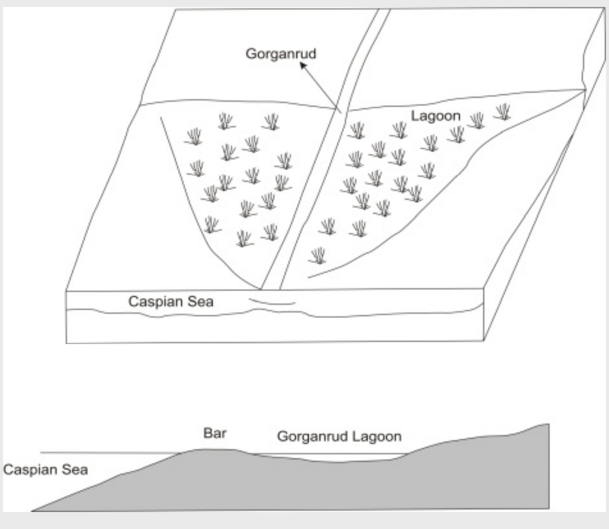
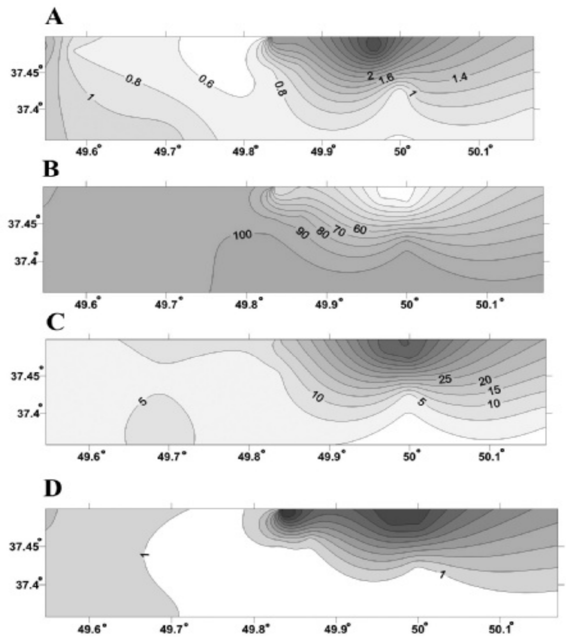


Figure 6- 3-D diagram of Gorganrud Delta.

Historical maps and data demonstrate that Gorganrud had two main distributary channels at a distance of 50 km from the Caspian shoreline. They entered to the sea from its eastern shoreline with a distance of 30 km. The northern channel was abandoned in the early twentieth century under the sea level fall. Now, the southern channel is the main channel of the Gorganrud River.

Sedimentology

Sedimentological studies have been carried out on the samples collected from delta surface and river mouth bars of the Sefidrud River. The West part of the river mouth is characterized by sandy bars that their thickness exceeds 10 m in some places. Silt and clay size fraction in the eastern side of the mouth gradually increases up to 30 %. The silt and clay size sediments transported to the sea during flooding stages are deposited on the shallow zones in the post-flooding stages. Organic matter content increases towards the eastern side up to 2 %. There is a local increase of organic matter in the sheltered western side of the Sefidrud (1 %). The grain size and organic matter distribution patterns are similar. Carbonate content in the surface sediments varies between 4 to 7 %. There is no significant trend between size distribution and carbonate content. The sedimentology of the Sefidrud River mouth is mainly controlled by the hydrodynamic processes. The distribution of sediment grain size and organic matter is closely related to the prevailed littoral drift which shifts them eastward (Figures 7).



A: TOC distribution around Sefidrud mouth (in percent)

B: Sand distribution around Sefidrud mouth (in percent)

C: Silt distribution around Sefidrud mouth (in percent)

D: Clay distribution around Sefidrud mouth (in percent)

Figure 7- Distribution pattern of surface sediments in Sefidrud Delta.

Analysis of surface sediment samples from 11 river mouths demonstrates that grain size distribution varies in a wide range from 0.001 to 20 mm. The spatial distribution of grain size reflects a pattern which is related to the source region and coastal slope. River mouths of the central coast have coarse grained materials (Chesmekile and Shiroud Rivers), while west and east coast river mouths are mainly composed of sand size sediments (Figure 8).

The Gorganrud River in the eastern part on the gently sloping coast that drains loose sediment of its valley has a muddy mouth.

Environmental Impact of Climate Changes and Human Activities

The Caspian Sea as a closed basin has a unique natural and some socio-economic features, whose interaction is subject to environmental tension (Golubev, 1996). It is obvious that human activities are major factors in the environmental changes, but nature is also capable of rapid and dramatic changes (Leroy, 2005). The Caspian Sea and its catchment areas experienced different environmental changes during the Quaternary period (Varushchenko *et al.*, 1987). Variations in humidity, precipitation, river influx and the sea level fluctuations have been the main consequences of the Caspian environmental changes (Klige, 1980; Meshcherskaya, 2001). The Caspian Sea as the world's largest land-locked water basin has drawn human attention since the late Pleistocene-early Holocene period coinciding with the early civilizations forming along the southern coast of Caspian Sea. Important sites in the eastern part of the South coast are Krasnovodsk, Ashghabad, Gorgan and Behshahr. In the western part Roudbar, Hashtpar and Baku are the identical points. They are mainly located above the Khavalyn Sea level from the Paleolithic to Neolithic ages (Ravasani, 1994). In the human-occupation sites, plentiful amounts of animal bones have been found which belong to species currently living in the Alborz forests. After the primary civilization which was scattered along the Caspian coast, the Persian, Hun, Khazar, Ottoman and Russian empires were the dominant powers in circum-Caspian region during succeeding historic eras. Iran, Russia and the newly-independent Republics of Turkmenistan, Kazakhstan and Azerbaijan which were formed after the collapse of the Soviet Union in 1991 are located on the Caspian coast. The population settling in the Caspian catchment area is estimated to be around 80 million, most of which lives in Russia (73 %), Iran (13 %) and Azerbaijan (10 %) (Lahijani, 2001) (Table 2).

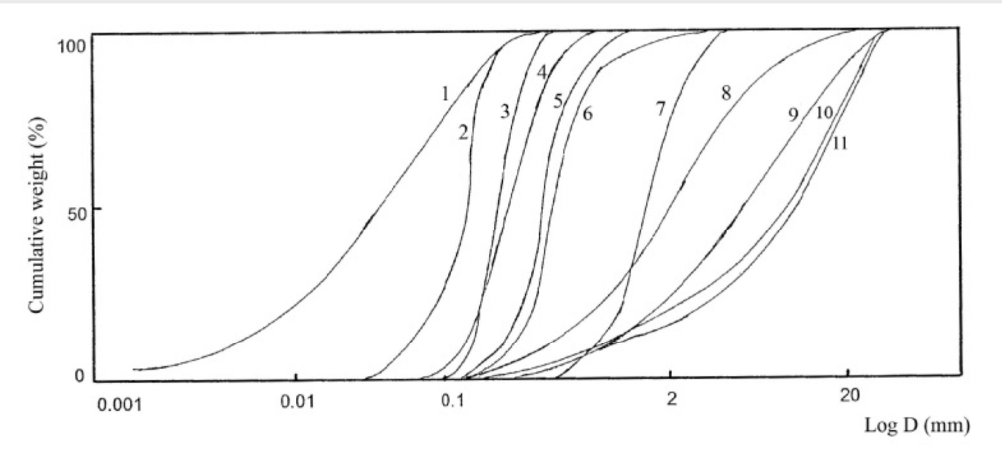


Figure 8- Grain size cumulative carves of the Iranian River mouths

Table 2- Description of circum-Caspian states

Country	Area of the country (Km^2)	Area located in Caspian watershed (Km^2)	Population of country (Million)	Population settled in Caspian watershed
Iran	1685000	185000	65	11
Turkmenistan	488100	400000	4.1	0.4
Kazakhstan	2717300	695000	17.1	0.4
Russia	17075400	1800000	148	60
Azerbaijan	86600	86600	7.6	7.6

Widespread human activities in the Caspian region deeply have affected its natural environment. Developments in industry, agriculture, fishery, marine transportation, and urbanization from the middle 20th century in the Caspian basin have increased the human impacts on the Caspian Sea (Komarov, 1996; Mikhailov, 1997). Both influencing factors, i.e. natural and human induced, control the river mouth configuration by changes in fluvial discharge and basinal parameters mainly of the sea level.

Sea level

The Caspian Sea level has changed repeatedly during its history as a lake (Federov, 1976; Rychagov, 1997). A significant fluctuation, from - 20 to -35 m, occurred in the Holocene period when the impacts of human activities on water balance were negligible. Instrumental measurements since 1880 have shown that the level has changed in amplitude of 3 m (Frolov, 2003) (Figure 9).

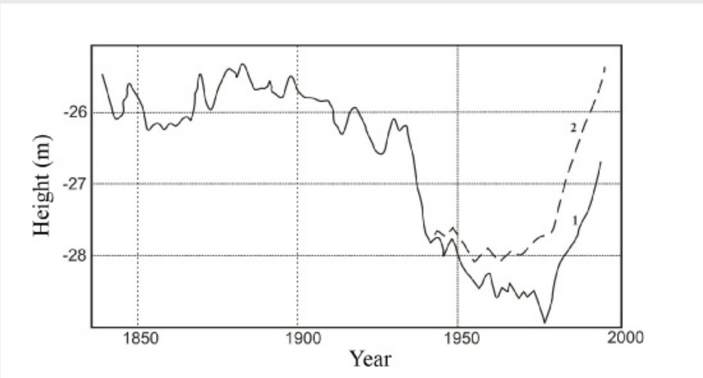


Figure 9- Caspian Sea- level curve during instrumental measurements (1) and reconstructed curve (2) with removing human impact since 1950s (after Frolov, 2003).

Recent fluctuation of the Caspian Sea level has been influenced by river influx, mainly from the Volga River (Rodionov, 1994). Since 1950, the Caspian catchment basin has been intensively changed by dam construction across the main rivers. Initially, the total volume of the reservoirs was around 150 km^3, 45 % of which were later filled by sediments (Figure 10).

Using freshwater for irrigation has reduced inflow to the Sea by the order of 42 km^3 per year. It seems that if there was no increase in river water use for economic growth of the circum-Caspian countries, the level of the sea would be 1.2 to 1.3 m higher than the present situation (Zonn, 1996).

Fluvial Discharge

Historical records show that humans have been intensively cultivating the coastal plain of the South Caspian since the past three centuries. Man not only expanded his agricultural territory, particularly rice fields, but also learned to build constructions for irrigation such as dikes across rivers, small soil dams known as *sals*, and modern hydraulic structures. In the coastal plain of the South Caspian Sea, diverting the rivers was the preferred method of water exploitation in past centuries. In this method, a small barrier was erected across the river and tiny channels were dug directing the water into the river sides. Development of the agricultural practices and type of agricultural products in coastal plain with a high demand for water has pushed the people to use a special type of water reservation known as a *sal* in the North of Iran. In fact, the *sals* are ancient soil dams in the southern part of the Caspian Sea and a constructional study on them could unveil the evolution process from soil *sal* to soil dam in the country. The *sals* are made in a crescent shape whose mouth faces the Alborz (South). The *sal* wall is made of clay and its head is situated at the same level with surrounding grounds and the outlet

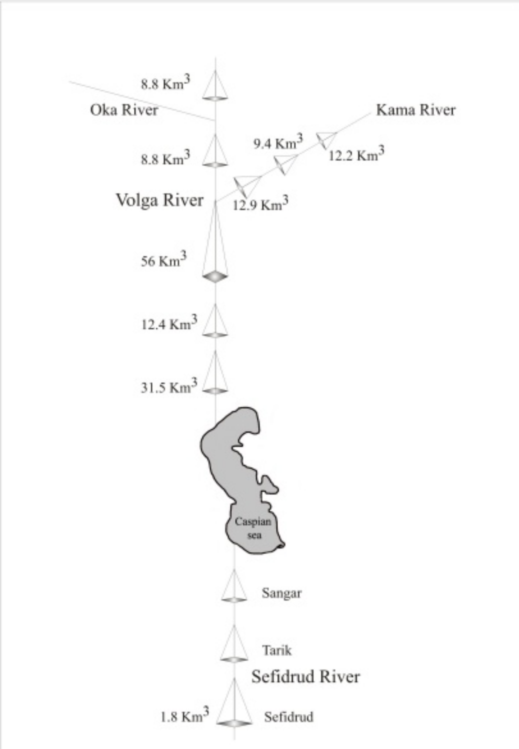


Figure 10- Main reservoir constructed across the Volga River, the largest water supplier and Sefidrud River, the largest sediment supplier to the Caspian Sea.

enjoys a 2 to 3 meter height. The *sal* wall is also used as the access road. The main function of the pond formed by the s*al* is the water reservoir but, over time, other functions such as fish culture have been added. The s*al*s could be regarded as a very appropriate pattern for development in the region (Figure 11).

Increasing freshwater demands for irrigation since the mid-20th century has pushed the government to construct dams across main rivers. The Sefidrud, Polrud, Haraz, Tajan, and Gorganrud Rivers are all regulated by hydraulic structures. The irrigation network appears to be responsible for a nearly 40% water loss in the river mouths. Most of the loss is accounted for by evapotranspiration in the irrigated fields of the coastal plain. Sedimentation in the reservoirs and sand excavating from river beds has reduced sediment discharge up to 50 % in moderate rivers. In the Sefidrud River, as the largest supplier of sediment, human activities have profoundly affected the coastal region, delta and river mouth. If the trend of sediment discharge reduction continues and accompanies with the sea level rise, we can expect the delta to evolve into a more wave-dominated form characterized by extensive beach, beach ridges, and dune formation, associated by substantial coastal retreat.

Comparison to Other Caspian River Mouths

The Caspian coasts in its northern, southern and western parts are modified by the river mouths (Leontiev *et al.*, 1977). Small rivers flowing into the Caspian Sea are mostly from the western and southern coasts, and produce simple river mouths. The configuration of the small river mouths deeply dependent on the fluvial discharge, coastal slope (both beach and near shore), and the nature of wave and wave induced currents. The sediment supply in these rivers is less than the potential wave energy of the receiving basin (Azimov *et al.*, 1986; Mikhailov, 1997; Voropaev *et al.*, 1998b).

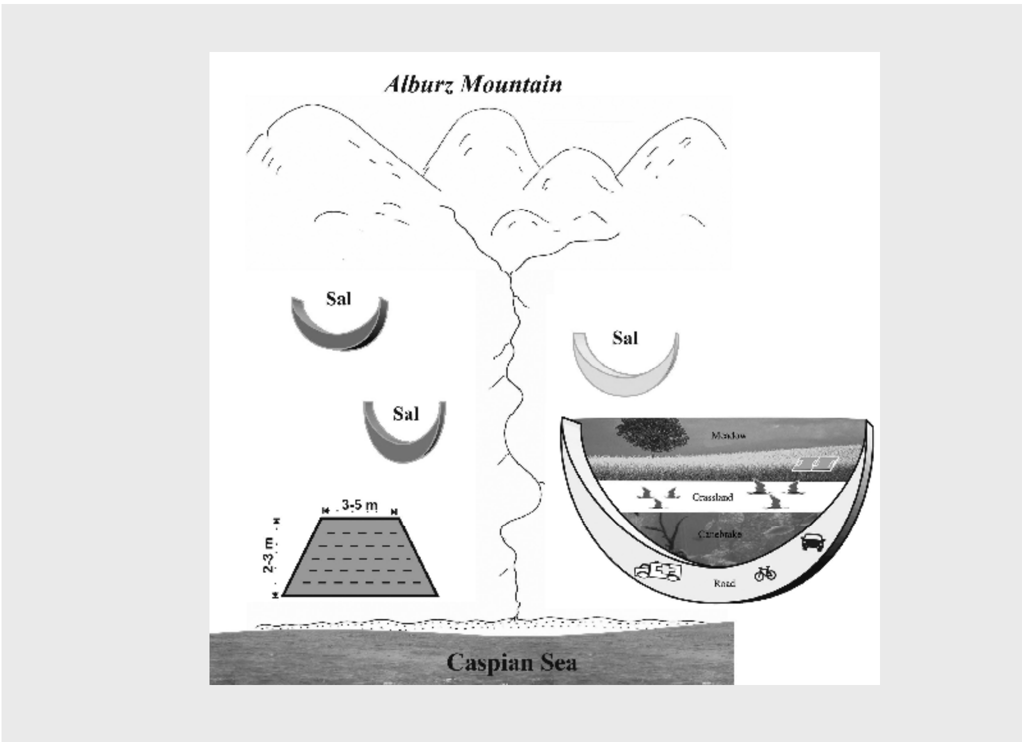


Figure 11. Old style water reservoir (soil dam or "Sal").

The balance between basinal and fluvial factors of the eight great rivers (Ural, Volga, Terek, Sulak, Samur, Kura, Sefidrud and Gorganrud Rivers) results in delta progradation into the Caspian Sea (Kroonenberg *et al.*, 1997; Krasnozhon *et al.*, 1998; Mikhailov, 1997; Voropaev *et al.*, 1998b). Their water and sediment discharge show that they are significantly different in terms of delta type and size (Table 3).

The Sefidrud, Kura and Terek Rivers supply large amounts of sediment, while other rivers (Ural, Volga, Samur, Sulak and Gorganrud Riivers) are less important in terms of sediment load (Mikhailov, 1997; Vorapaer et al, 1998). The Gorganrud's inflow is around 0.5 km^3 annually, which is 0.22 % of the Volga River's discharge (233 km^3). There are different basinal conditions, which allow for delta evolution of a river (Figure 12).

Table 3. Caspian deltaic rivers and their specifications.

River	Length (Km)	Drainage area (1000 km^2)	Water (Km^3/y)		Sediment (mt/y)	
				*		*
Volga	3690	1360	243	233	14	6
Ural	2430	237	7	6.6	2.7	-
Terek	623	43.2	8.9	8.4	15.1	11.9
Sulak	169	15.2	4.4	4.0	13.2	1.6
Samar	213	7.73	-	1.63	-	4.7
Kura	1360	188	17.8	15.5	39.7	17.1
Sefidrud	800	67	5	4	40	32
Haraz	185	4.1	1.2	0.5	3	1
Gorganrud	350	12.6	0.5	0.3	4	2.5

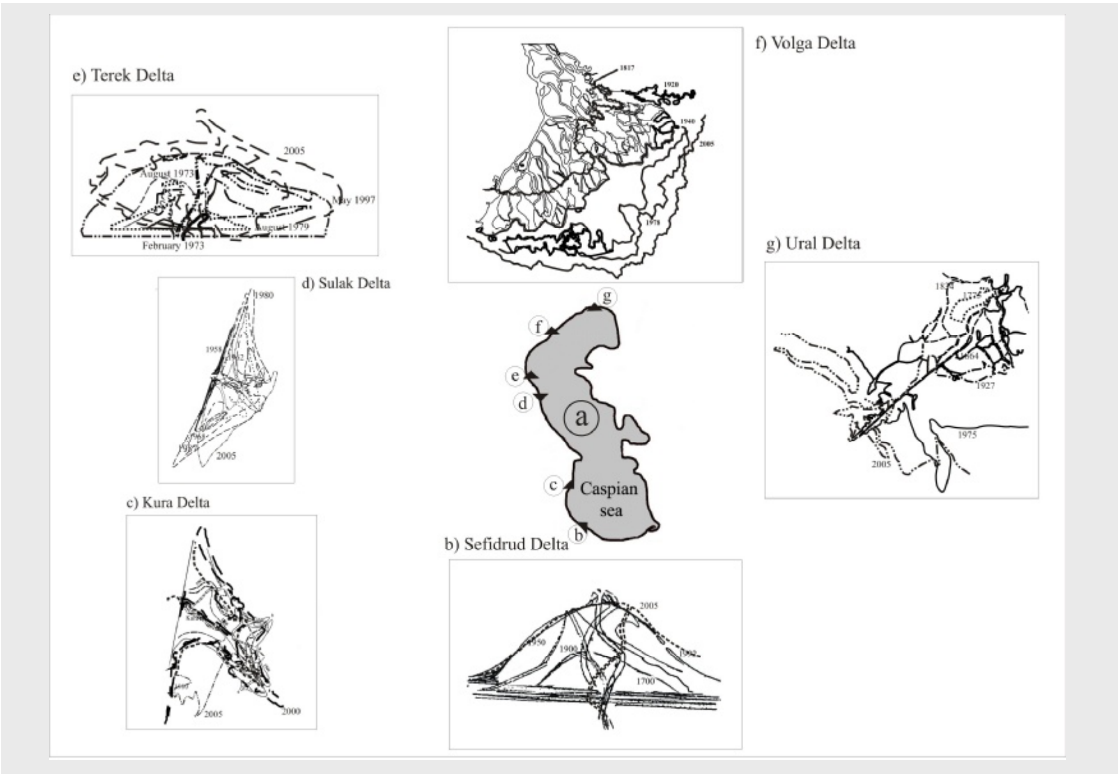


Figure 12- Main evolution stages of the Caspian great deltas:

(a): Location map of the deltas.

(b): Sefidrud Delta (after Lahijani, 1997; Krasnozhon, 1998; Lahijani et al., 2007).

(c): Kura Delta (after Alekseevskii et al, 1983; Mehdiev, 1966)

(d): Sulak Delta (after Leontiev and Khalilov, 1962; Leontiev, Maev and Richagov, 1977)

(e): Terek Delta (after Leontiev, Maev and Richagov, 1977; Mikhailov, 1997)

(f): Volga Delta (after Kroonenberg, Rusakov and Svitoch, 1997; Mikhailov, 1997)

(g): Ural Delta (after Krasnozhon, 1985; Polonskii, Lunachev and Skrintunov, 1992)

The Ural and Volga Rivers enter into the northern Caspian sub-basin that has a gently sloping continental shelf (Lebedev *et al.*, 1987). The gradient of the continental shelf towards the west side of the northern Caspian Sea into which the Terek and Sulak Rivers flow gradually increases. A steeply sloping continental shelf and near shore is the dominant feature in the West and South Caspian Sea, in the areas where the Samur, Kura and Sefidrud Rivers enter into the sea (Leontiev *et al.*, 1977). The Gorganrud River reaches the sea from its southeastern corner with a low gradient shelf (Lahijani, 1997) (Figure 13).

The morphological characteristics of the Caspian coastline and its shelf control the way that basinal forcing factors act against the river mouths. The shallow and wide shelf on the northern Caspian prevents high wave development. During winter, the basinal forcing factors are inactive as the basin wholly freezes (Terziev, 1992). Because of the low gradient of the northern basin, the Volga and Ural deltas are sensitive to short- and long-term sea level changes. In this region, a river dominated delta could develop. In the western and southern Caspian Sea, waves and wave-induced currents are the main forcing factors that contribute to the delta configuration. The strong long shore current determines the shape of delta growth into the sea, as can be seen in the mouths of the Sulak, Samur, Kura and Sefidrud Rivers (Krasnozhon *et al.*, 1998; Leontiev *et al.*, 1977; Mehdiev, 1966; Mikhailov, 1997) (Figure 12).

In north part of the Kura Delta cross-shore currents are dominant due to a prevailng near perpendicular to perpendicular wave approach. Southeastward littoral drift determines the enlargement of the Kura in the same direction. In Zidostovi Kultuk Bay, South of the Delta and with a special shoreline configuration, the combination of opposite directions of littoral drift and cross-shore transport between them could be seen. The pattern of approaching waves and corresponding currents continue to dominate the erosion processes in the northern part of the Delta and accretion in the southern Bay (Mehdiev, 1966). The South coast of the Azerbaijan region consists of sandy deposits while, in the Kura Delta, mud strips are distributed along the shore between silty sands and muddy sands. The origin of mud in the north part of the delta seams to be from older deposits whereas in the southern delta, the muddy deposits come from the Kura River (Mehdiev, 1966). After the reinvasion of the Kura River in 1960, its sediment load decreased at a range of 40 %, then the 100 m/y progradation of the delta has changed to a 15-20 m retrogradation (Leontiev and Khalilov, 1962). Comparison of the potential wave energy of the Kura region (Azimov *et al.*, 1986; Mehdiev, 1966) with the fluvial supply (Coleman and Wright, 1975) indicated that waves and wave-induced currents play an important role in development of the Kura Delta. Some similarities between the Mississippi and Kura Deltas can be attributed to the domination of fluvial

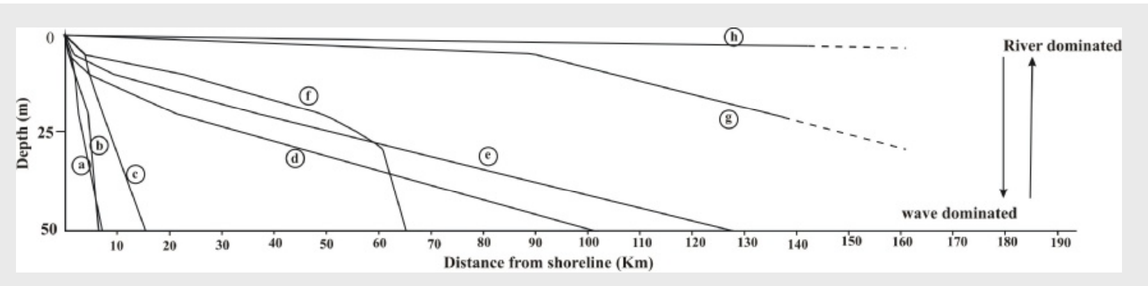


Figure 13- Cross- shore bottom profiles of the Caspian deltas.

(a): Samur	**(b): Sefidrud**	**(c): Kura**
(d): Sulak	**(e): Terek**	**(f): Gorganrud**
(g): Volga	**(h): Ural**	

processes in the Kura Delta (Hoogendoorn *et al.*, 2005). The Gorganrud River is the smallest deltaic river of the South Caspian Sea. It enters into a low energy area that provides the necessary conditions for delta formation.

The water level of the Caspian Sea has fluctuated significantly after its separation from the Black Sea. The location of the delta is greatly related to the Caspian Sea level. The old deltaic deposits could be traced in land up to +140 abs and, in the sea bottom, down to -70 abs m (Leontiev *et al.*, 1977; Varushchenko *et al.*, 1987). When sea level rises, the deltas retrograde landward and, during a sea level fall, they prograde into the sea. A stable sea level or little fluctuating of it provides proper condition for delta evolution in the Caspian Sea (Mikhailov, 1997). A rising sea level since 1979 has caused inundation and erosion of the Caspian deltas (Voropaev *et al.*, 1998a). Fluvial dominated deltas (Ural, Volga, Terek and Gorganrud) are characterized by inundation, while wave dominated deltas (Sulak, Samur, Kura and Sefidrud) are affected by erosion processes (Figure 12). Impacts of human activities, such as the reduction of fluvial discharge, accelerates erosion and inundation of the Caspian deltas. River regulation, diversion and modification have fundamental impacts on the fish production of enclosed and semi-enclosed basins (Drinkwater and Frank, 2006). A reduction in freshwater influx could contribute to the changes on the physical, chemical and biological processes of the river mouth and adjacent environment. Historically the Caspian Sea has been known for its sturgeon and was rich in many other commercial species. From the end of twentieth century, catches of commercial species declined due to intensive human activities in the Caspian Sea and its catchment basin. Rever regulation, pollution, overfishing, invasion by alien species and sea level fluctuation have all contributed to the fish decline (Khodorevskaya *et al.*, 1998; Alekseevskii *et al.*, 1997; Katunin, 1997). In general, all 130 rivers flowing into the Caspian Sea have experienced regulation in different levels. The Iranian rivers with their small to moderate discharge in comparison to the North Caspian rivers are more sensitive to water consumption. High freshwater demand by rice and cotton fields in the spring and early summer seasons causes a sharp decrease of the river discharges. At the same time wave action on the beaches, which creates sandy barriers across some rivers, prevents fish migration. Build-up in the river bed near bridge piles for decreasing erosion, are the major obstacle for the migration route. An intensive restocking program is performed annually to compensate for the negative impact of river regulation on its fishery (*Sal*ehi, 2003; Ramezani, 2003).

Conclusion

The South Caspian river mouths exhibit a wide range of configurations. Their forms and geometry largely depend on the fluvial discharge and characteristics of the receiving basin. The south Caspian coast differs in slope, dominant wave regime and coastal currents, which modify the river mouths. The river mouths of the Iranian coast on the based of their morphology could be classified into three groups, and the small rivers do not have sharp river mouths entering the Caspian Sea but they disappear into the coastal plain or enter into the coastal lagoons. Medium-sized rivers flowing to the Caspian Sea display three types of river mouths:

1- A river mouth inclined to the direction of the prevailing long shore drift;
2- A river mouth with a lateral lagoon and small mouth bar;
3- A coarse grained river mouth.

Great rivers, as far as sediment discharge is concerned, form deltas into the Caspian Sea. A gently sloping shelf and near shore in the southeastern corner of the Caspian Sea provides a low energy environment for developing the Gorganrud Delta.

The Sefidrud River as the largest sediment supplier to the South Caspian Sea and it develops its delta in a high energy and high gradient coastal area with strong littoral drift. The modern delta has been formed since river avulsion around 1600 AD.

Waves and wave-induced currents determine the morphology of the Sefidrud Delta. The combined impact of the human activities and Caspian Sea level rise during the past decades accelerated inundation and erosion of the river mouth area. Inundation and erosion are prominent in the high and low gradient coasts, respectively.

The Caspian deltas are distributed along the northern, southern and western coasts. Their shape and morphology have been determined by the shelf gradient and wave energy under the highly variable Caspian Sea level.

Consequently, the Caspian deltas show a range from river-dominated (Volga) to wave dominated (Sefidrud) morphology. The sea level rise facilitates transitional deltas along the northwest Caspian (Sulak and Samour) to receive more wave energy.

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