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WATER RESOURCES AND THE REGIME OF WATER BODIES

The Response of River Mouths to Large-Scale Variations in Sea Level and River Runoff: Case Study of Rivers Flowing into the Caspian Sea

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Abstract—Regularities in the response of the mouths of major rivers, flowing into the Caspian Sea, to large-scale variations in its level and river water runoff and sediment yield are considered. Changes in the morphological structure and hydrological regime of the Volga, Terek, Sulak, Ural, and Kura mouths have been analyzed in both geological past and separately for three modern periods: a considerable drop in Caspian Sea level before 1978, its abrupt rise in 1978–1995, and a relative stabilization in the subsequent years. Specific features were identified in the hydrological–morphological processes in different mouths, caused by the differences in river sediment yields, and the slopes of delta surface and mouth nearshore beds. Some theoretical and methodological approaches were verified in the analysis and evaluation of the processes under consideration. The obtained results of studies of the mouths of rivers flowing into the Caspian Sea can be regarded as examples and analogues in the assessment of processes, which take place at the mouths of other Russian and world rivers at present and can take place in the future under anticipated natural and anthropogenic variations in sea level and river runoff.

Keywords: river, sea, mouth, delta, nearshore area, river runoff, sea level.

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INTRODUCTION

The Caspian Sea is the largest on the Earth in the current geological epoch closed inland water body with varying level, receiving >130 large, medium, and small rivers [18]. The largest among them are the Volga (the largest river in Europe), Ural, Terek, Sulak, and Kura. These rivers account for >92% of water runoff of all rivers (~300 km^3/year) flowing into the Caspian Sea [30].

River mouth areas (RMA, a synonym is *river mouths*) are the most variable elements of the coastal zone of any receiving water bodies (oceans, seas, or lakes), including the Caspian Sea. Generally, they show a fast and strong response to the natural and anthropogenic changes in water runoff and sediment yield and to water level in the receiving water body. On the Caspian Sea coast, such are primarily the RMAs of the Volga, Ural, Terek, Sulak, and Kura.

Variations in the morphological structure and hydrological regime of the mouths of those rivers have long attracted the attention of geographers, environmentalists, hydrologists, oceanologists, geomorphologists, engineers in different economic fields, and experts in nature protection. This can be attributed to two major causes. First, the development of rich land, water, biological, and mineral resources at the mouths of the Volga, Terek, Sulak, Ural, and Kura, situated in densely populated and economically developed regions of the former USSR (now, the southern parts of Russia, Kazakhstan, and Azerbaijan), would be impossible with no allowance made to the natural conditions of the features under consideration, primarily, their hydrological, morphological, and environmental conditions and their variations. Second, the mouth areas of those rivers, especially, their deltas, are very variable natural objects, which develop in the course of specific mouth processes. Their variability is aggravated by a strong effect of external factors—natural and, especially, anthropogenic variations in water runoff and sediment yield and considerable variations in Caspian Sea level. The permanent and considerable changes in the hydrological, morphological, and environmental conditions at the mouths of Caspian rivers require their permanent studying, assessing, and forecasting.

Among the rivers flowing into the Caspian Sea, the greatest attention has been always paid to the delta and nearshore zone of the Volga—the main river in European Russia. Three periods can be identified in the studies of this object: the period before the World War II, when the delta was studied for the first time [13]; period 1950–1980, when researchers from State Oceanographic Institute (SOI) in cooperation with local institutions of hydrometeorological service [6–8, 59], State Hydrological Institute (SHI) [62], and Astrakhan Reserve [10, 11] collected a vast body of data on this object; the late XX–the early XXI, when studies were carried out by Geographic Faculty, MSU; SOI, and Water Problems Institute, RAS (WPI RAS) [3, 20, 21, 27, 33, 36, 41, 43, 47, 50–52, 57, 61, 64, 65, 68]. Extensive investigations were also carried out (mostly by SOI, MSU, and WPI RAS) at the mouths of the Terek and Sulak rivers [1, 2, 4, 9, 12, 17, 24, 28, 35, 38, 40, 44–46]. Less studied are the processes in the deltas of the Ural [25, 26, 51, 60] and the Kura [1, 16, 19, 34, 63]. The results of studies at the mouths of the Volga, Terek, Sulak, Ural, and Kura were reviewed and generalized in [30, 36, 37, 68].

The studies mentioned above have analyzed variations in the hydrological regime and delta formation processes at Caspian river mouths mostly in the period when its level was dropping (up to year 1978) and in 1980–1990. The changes in the structure and regime at river mouths in the period when the sea level was rapidly rising (1978–1995) have received much less attention.

However, those studies provided unique data reflecting the response of river mouths to considerable and differently directed changes in Caspian Sea level and to anthropogenic variations in river runoff. They have created the conditions for scientific generalization of the obtained data and the identification of universal regularities in the response of river mouths to changes in the external factors—river water runoff and sediment yield and sea level. The analysis of such regularities and the development of appropriate methods for the evaluation and forecasting of mouth processes under changing natural conditions are gaining in importance under current conditions of global climate changes [15, 37, 39, 66, 68] and the accompanying level rise in the World Ocean, river runoff variations, the greater impact of marine factors on deltas, etc. The experience in studying the processes that cause changes in the structure and regime at river mouths in the Caspian Sea, as analogues of the processes expected to take place in the XXI century at the mouths of other rivers in Russia and the World, can become extremely important. The generalization of such experience, which is of not only regional, but also more general significance, is the objective of this study.

The paper is based, primarily, on the results of regional studies at the mouths of rivers flowing into the Caspian Sea. Also used were data on large-scale variations in Caspian Sea level [22, 53–56], geomorphologic data on Volga valley and Caspian shores both at present and in geological past [14, 22, 29, 47–49, 55, 56, 58, 63], materials on natural and anthropogenic variations in the runoff of rivers flowing into the Caspian Sea [5, 15, 18, 30], and on the current hydrological regime of the Caspian Sea [18].

RAW MATERIALS AND METHODS OF STUDIES

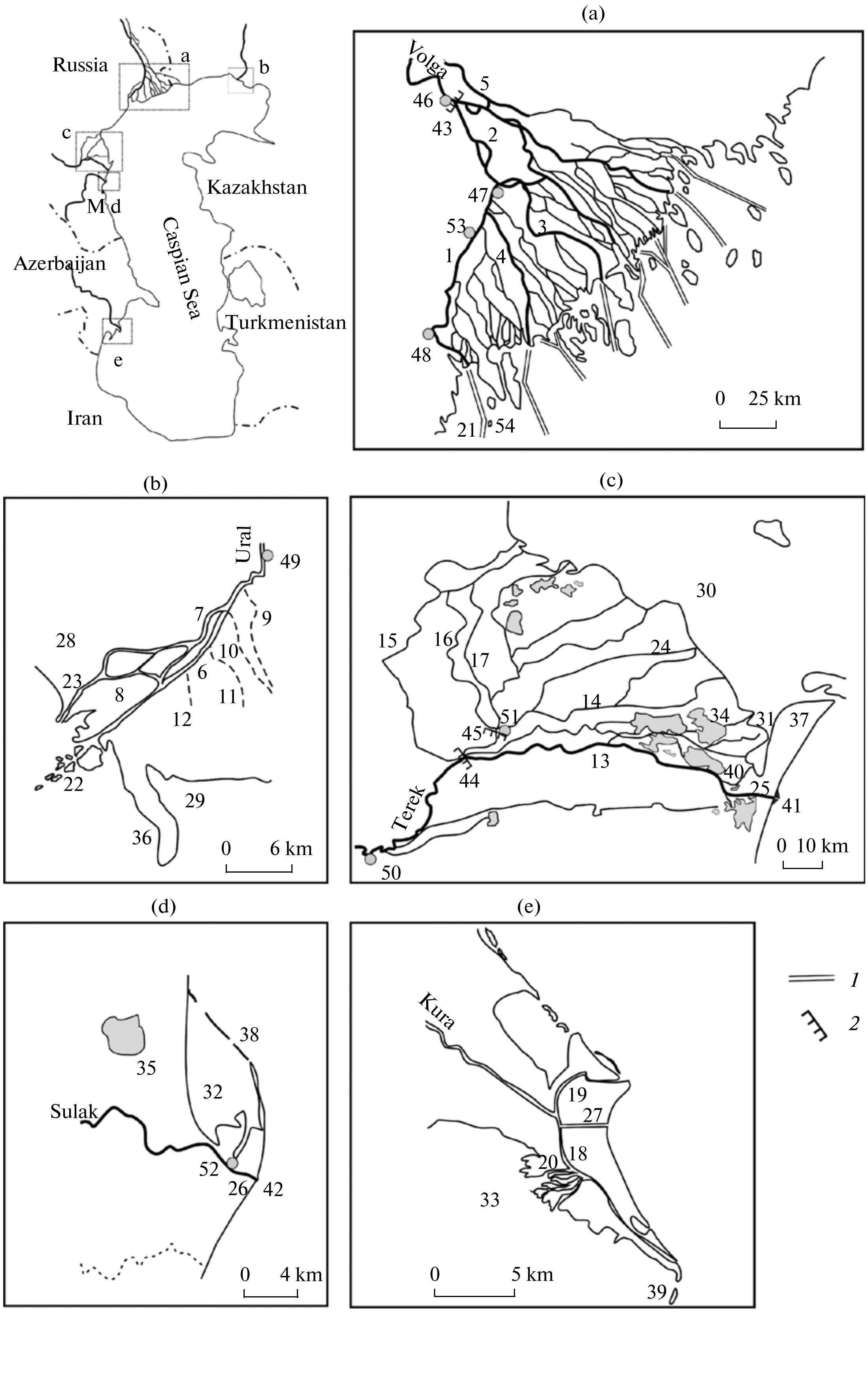
In the analysis of the variations in the structure and regime of Caspian river mouths, the authors use various methods of studies and a vast body of raw data.

The studies of water runoff and sediment yield variations over time and their redistribution over delta areas, water level variations in the Caspian Sea and at river mouths were based on long-term observational data on water flow Q, suspended sediment discharge R, and water level H at gauges. Part of materials were collected during expedition studies (in some cases, with the participation of the authors) or taken from the literary and archive sources. All data series were verified and gaps in them were filled. To analyze variations in water level in the deltas, empirical relationships of the type of $H_i = f(Q, H_s)$, where H_i are water levels at gauges, Q is water discharge in a river or a delta branch, H_s is sea level. Sea level H_m was taken from the Makhachkala sea gauge for all objects, and, in the case of the Volga, the value from the gauge near the delta coastline (DCL) (Iskusstvennyi Island) was also used.

Vast cartographic materials for the deltas of the rivers under consideration were systematized and converted to the same scale. The scale of all topographic maps and schemes of deltas was determined more accurately or evaluated anew based on well-known points. Aerial photographs were transformed to Gauss–Krüger projection. Space photographs were also digitized and interpreted using an ad hoc procedure for the analysis of delta dynamics on space pho-

Fig. 1. Schemes of the modern mouth areas of the rivers of (a) Volga, (b) Ural, (c) Terek, (d) Sulak, and (e) Kura.

Branches and bypasses: (1) Bakhtemir, (2) Buzan, (3) Bol'shaya Bolda, (4) Kizan (Kamyzyak, (5) Akhtuba, (6) Zolotoi, (7) Yaitskii (Yaik), (8) Shman-Uzek, (9) Peretaska, (10) Bukharka, (11) Zaroslyi, (12) Zolotenok (b), (13) Kargalinskii Proryv, (14) Old Terek, (15) Sulu-Chubutla, (16) Borozdinskaya Prorva, (17) Talovka (c), (18) Southeastern, (19) Northeastern, (20) Southwestern (e); canals: (21) Volga–Caspian (a), (22) Ural–Caspian, (23) fish migration canal (b), (24) Kizlyar–Caspian, (25) cutoff through Agrakhanskii Peninsula (c), (26) straightening cutoff in Sulak delta (d), (27) new canal in the Kura delta (e); bays: (28) Atamanskii Kultuk, (29) Zolotinskii Kultuk (b), (30) Kizlyarskii, (31) Agrakhanskii, (c) (32) Sulak Bight (d); (33) Zyuid-ostovyi Kultuk (e); lakes: (34) Terskie (c), (35) Mekhteb (d); peninsulas and spits: (36) Peshnoi (b), (37) Agrakhanskii (c), (38) Sukakskaya Spit (d), (39) New Kurinskaya Spit (e); particular deltas: (40) Alikazgan, (41) New Terek Delta (c), (42) New Sulak Delta (d), water engineering systems and dams: (43) Volga water divider (a), (44) Kargalinskii water engineering system, (45) Kopaiskii water engineering system (c); towns and populated localities: (46) Verkhnee Lebyazh'e, (47) Astrakhan, (48) Olya (a), (49) Atyrau (former Gur'ev) (b), (50) Stepnoe, (51) Kizlyar, (52) Sulak (d), (53) Ikryanoe (a), (54) Iskusstvennyi Island (a). M is Makhachkala marine gauge. (*1*) Navigable and fish migration canals at Volga nearshore mouth area, (*2*) water-engineering systems and dams.


Russia
a
b
c
M
d
Kazakhstan
Caspian Sea
Azerbaijan
Turkmenistan
e
Iran
(a)
Volga
5
46
43
2
47
53
3
1
4
48
21
54
0 25 km
(b)
Ural
49
7
9
28
10
23
6
8
11
12
22
29
36
0 6 km
(c)
30
15
16
17
24
14
51
34
31
37
45
13
44
40
25
41
Terek
50
0 10 km
(d)
38
35
32
Sulak
52
26
42
0 4 km
(e)
Kura
19
27
18
20
33
0 5 km
39
1
2

tographs [23]. The cartographic materials transformed to the same scale were used as a basis for compiling a series of maps of the Ural, Terek, Sulak, and Kura deltas for different times. The morphometric characteristics of river deltas were determined with the use of up-to-date computer technologies. The denotations used in the study are as follows: L is delta length along the main channel, km; F is delta area, km^2; B_{DCL} is the length of delta coastline, km.

Analysis of the processes taking place at river mouths and their approximate calculation and prediction were carried out with the use of the theory of mouth hydrological–morphological processes [31, 32, 41, 42, 51, 64, 67], methods of river hydraulics (considering the specific mouth processes) [31, 40, 42], equations of sediment balance at river mouths [2, 31, 41, 46], and the hydrological–morphometric relationships for the calculation of stable characteristics of the flow and channel and the identification of trends in channel processes in deltas [31, 32, 42, 43].

BACKGROUND DATA ON THE MOUTHS OF MAJOR RIVERS FLOWING INTO THE CASPIAN SEA

The RMAs of the rivers of Volga, Ural, Terek, Sulak, and Kura (Fig. 1) are unique geographic objects with their peculiar structures, hydrological regimes, and environmental conditions, as well as very rich natural resources—land, biological, and mineral.

The main morphological parts of all five RMAs under consideration are large deltas. The deltas of the Volga and Terek are the largest in Europe with the areas of ~11 and 8.9 thousand km^2, respectively. The Volga delta, one of the most braided in the World, ranks next to the Lena delta in Russia. The authors determined the outer boundaries of RMA based on the following principles. If level rise during medium-size storm surges at low river flow does not travel upstream of the delta head (DH) (as is the case with the Volga and Terek mouths), the DH is take as the upper (river) boundary of RMA. Otherwise, i.e., if the surges travel over the near-delta part of the river upstream of DH, the upper boundary of RMA is taken to be the point to which medium-size surge reach in periods of low flow in the river. Thus, RMA upper boundary for the Ural, Sulak, and Kura lies about 150, 30, and 40 km upstream of DH, respectively. This segment upstream of DH is referred to as river mouth segment.

The upper boundary of Volga RMA, which coincides with DH, is the site where the large left branch Buzan, separates from the main river channel (near Verkhnee Lebyazh'e Vil.) (Fig. 1a). The Buzan receives the large floodplain branch Akhtuba. Near Astrakhan City, the large branches of Krivaya Bolda and Pryamaya Bolda (they merge into the Bol'shaya Bolda branch further downstream), Kizan (Kamyzyak), and Old Volga separate from the main river branch—the continuation of the Volga. The channel of the main branch is farther referred to as the Bakhtemir. This branch continues into the nearshore zone as the navigable Volga–Caspian Canal (VCC) ~100 km in length. With the aim to control the runoff distribution between the western and eastern parts of the Volga delta, the Volga Water Divider was constructed in its DH and a longitudinal dike, along the delta. Some delta branches continue to the nearshore area as raceways (Fig. 1a).

The head of the Ural delta (~300 km^2 in area) was previously the site where the left bypass Peretaska separates from the main channel 6.2 km downstream of Atyrau Town (previously, Gur'ev Town) (Fig. 1b). However, because of the dying of this bypass, the main node of the delta channel network has become the place of river separation into two large branches: the right Yaitskii (Yaik) branch, which forms a system of several branches, and the left Zolotoi branch. The Zolotoi branch is the main delta branch; it continues as the Ural–Caspian Canal (UCC) in its lower part.

The Terek delta begins 170 km from the sea near Stepnoe Village and forms a vast plain slightly sloped northeastward and having a cellular character (Fig. 1c). The hydrographic network of the delta is complicated by numerous branches, bypasses, irrigation and drainage canals, lakes, and flooded areas. Until the mid-1970s, the main branch of the delta, the Kargalinskii Proryv, emptied into the shallow Agrakhanskii Bay, while since August 1977, it empties directly into the Middle Caspian Sea through an artificial cutoff through Agrakhanskii Peninsula. A small delta, referred to as the New Delta of the Terek, has formed at the branch inflow into the sea.

The modern Sulak delta (44 km^2 in area) is an asymmetric accumulation protrusion, consisting of the active southeastern lobe with active main river channel and dead delta lobes north of it (Fig. 1d). In the lower part of the delta, river channel passes through an artificial cutoff dug in 1957. A small New delta of Sulak has formed at the mouth of the cutoff. Sulak spit separates Sulak Bay from the sea.

The Kura delta (138 km^2 in area) ranks fourth on the coast of the Caspian Sea in terms of its size. It is a part of Kura–Araksinskaya Lowland. Similar to Sulak delta, the modern Kura delta has a typical shape of a lobe protruded far in the sea (Fig. 1e). The hydrographic network of the delta in the late XX century consisted of two branches—the Southeastern Branch (Navigable Kura) and Northeastern Branch (Old Kura).

The RMA also includes nearshore areas as parts of the coastal zone of the sea (Fig. 1). All nearshore areas of Caspian rivers are now open, but have different size and refer to different types in terms of the degree of their boldness or flatness. The Volga mouth has an extremely wide nearshore area, the mouths of the Ural, Sulak, and Kura have narrower nearshore areas, and that in the Kargalinskii Proryv Branch of the Terek is very narrow. The nearshore area at Sulak and Kura

Table 1. Water runoff W_Q and sediment yield W_R and mean water turbidity in rivers flowing into the Caspian Sea (given in parentheses are re-established values)

River (gauge)	Period	W_Q, km^3/year	W_R, million t/year	s, g/m^3
Volga (Verkhnee Lebyazh'e)	1881–1955	(245)	(12.8)	(52)
	1956–1960	239	12.7	53
	1961–2006	250	6.7	27
	1978–1995	273	8.5	31
Ural (Topoli, Makhambet since 1973)	1921–1957	9.2	(3.0)	(326)
	1958–2007	8.3	2.7	325
	1978–1995	9.0	2.8	311
Terek (Stepnoe)	1924–1956	10.1	(21.2)	(2100)
	1957–2007	9.0	(16.9)	(1880)
	1978–1995	8.7	15.0	1720
Sulak (Sulak)	1925–1974	(4.8)	(14.7)	(3060)
	1975–2007	4.7	1.8	383
	1978–1995	4.5	1.7	377
Kura (Sal'yany)	1927–1952	(17.8)	(34.6)	(1940)
	1953–2000	(14.1)	(15.8)	(1120)
	1978–1995	(13.8)	(11.4)	(826)

mouths and near the New Delta of the Terek is very bold (its bed slope $i_{nsh} > 1‰$); at the Ural mouth, the nearshore area is moderately flat (i_{nsh} from 0.01 to 0.1‰), and that at the Volga mouth is very flat ($i_{nsh} <$ 0.01‰).

The natural resources of Caspian river mouths are in wide use in agriculture and fishery. Important navigation routes pass through the mouths of the Volga and Ural. A large industrial and port center Astrakhan, the center of the province, is situated in the Volga delta. Kizlyar Town, a large center of agricultural production, is situated the in Terek delta. In addition to economic, the mouths of Caspian rivers are of extreme environmental significance as the sites of spawning and fattening of valuable fish species, the growth of diverse and rich vegetation (e.g., reed, lotus), hibernation and nestling of birds, etc. Biosphere reserves are situated in Volga and Kura deltas.

Details data on the current state of the mouths of major Caspian rivers as specific geographic objects are given in [12, 16, 17, 30, 34–36, 51, 61].

THE EXTERNAL FACTORS AFFECTING RIVER MOUTHS IN THE REGION

The major external factors that determine the character of the present-day hydrological–morphological processes at the mouths of major Caspian rivers are river water runoff and sediment yield, sea level variations, and sea waves. River sediment yield and its variations form the main factor that determines the rate of increase in the mouth cone and delta protrusion. Long-term sea level variations either facilitate delta protrusion into the sea (during sea level drop) or hamper such protrusion and sometimes even lead to the inundation of parts of deltas (during sea level rise). Sea waves destroy delta deposits and change the outline of delta coastline.

River Water Runoff

Approximate estimates of river runoff contribution to the water balance of the Caspian Sea in the XX century on the average are as follows. The water input includes river water runoff (~300 km^3/year), precipitation onto water surface (~74 km^3/year) and groundwater runoff (~4 km^3/year) with a total of ~378 km^3/year. River runoff accounts for 79% of the water input. Volga runoff (~250 km^3/year, 83% of the total river runoff) accounts for ~60% of the water input. The mean water runoff is ~9 km^3/year for the Ural River (3% of the runoff of all rivers), ~9 (3%) for the Terek, 4.5 (~1.5%) for the Sulak, and ~14 km^3/year (~5% of the runoff of all rivers) for the Kura (Table 1). The five largest rivers of the Caspian region considered in this study give on the average the total of 286.5 km^3/year or 96% of the total river runoff and ~76% of water input.

Analysis of long-term variations in Caspian river runoff (Table 1) allows us to identify several characteristic periods, whose boundaries are mostly determined by large-scale hydroengineering construction and the dynamics of water use in river basins. In the case of the Volga (Fig. 2a) these are the following three main periods [61]: 1881–1955, the period of natural runoff regime; 1956–1960, the period of filling of large

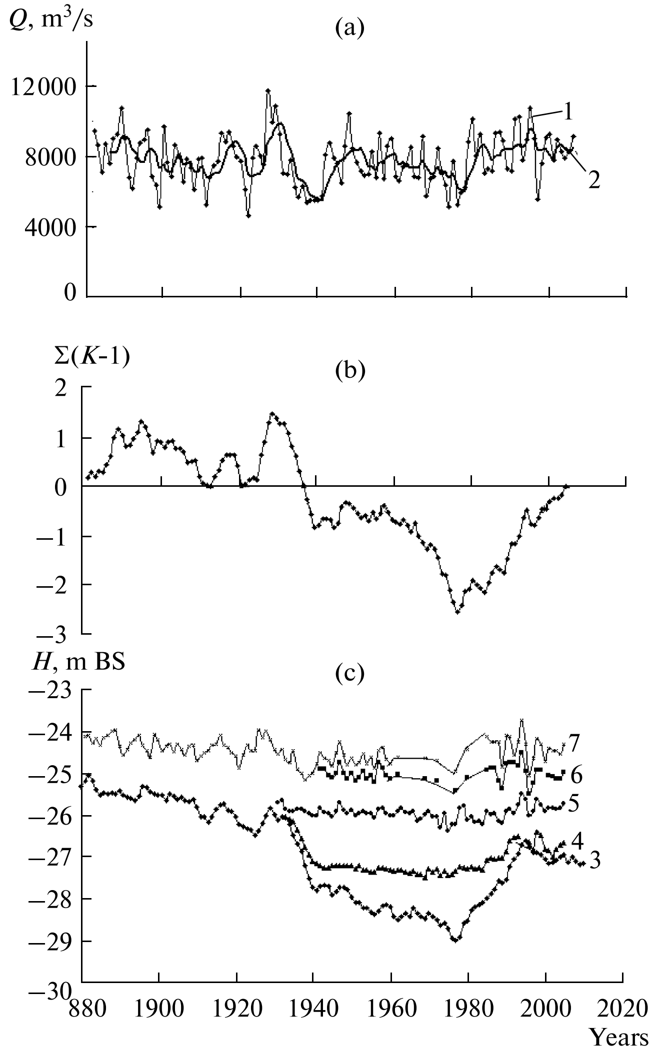


Fig. 2. (a) Long-term variations in (1) the annual and (2) 5-year moving mean Volga water discharges at Verkhnee Lebyazh'e gauge; (b) accumulated normalized deviations of annual water discharges at the Volga delta head from their long-term mean; (c) variations in annual water levels of the Caspian Sea at (3) Makhachkala and at gauges at the Volga mouth: (4) Iskusstvenny Island (27 km offshore the DCL), (5) Olya (24 km upland from the DCL), (6) Ikryanoe (73 km from the DCL), (7) Astrakhan (111 km from the DCL) (7).

Volga–Kama reservoirs with a total volume of 109.76 km^3; since 1961 to the present time, the period of regulated regime and partial withdrawal of Volga runoff. In the case of the Sulak and Kura, these are periods before and after the construction of the Chirkey (1974, full volume of 2.78 km^3) and Mingechaur (1953, 15.73 km^3) reservoirs [16, 17]. The mean annual runoff of the Ural in individual periods varied only slightly. The criteria in the isolation of periods in Terek runoff variation are the construction in 1957–1958 of Tersko–Kumskii canal, Kargalinskii (1956) and Kopaiskii (1959) hydrosystems in river delta, and the dynamics of water withdrawal in river basin and its abrupt increase since the late 1950s. Additionally, runoff characteristics were calculated for all rivers for 1978–1995—the years of considerable sea level rise.

The long-term variations in annual water runoff in Caspian rivers show the following major regularities and features. Volga runoff demonstrates a larger role of natural (climate-induced) variations and a smaller effect of economic activity in its basin as compared with other rivers. This fact is confirmed by data of the last decades of the XX century, e.g., a considerable increase (since 1978) in the total annual water runoff, notwithstanding the largest volume of water consumption in the basin in 1970–1980.

According to forecasts made in SHI with the use of climate models, Volga water runoff can increase by 2–3% by year 2030. However, the analysis of cyclic oscillations in water runoff yielded somewhat different estimates: the water runoff of the Volga, Ural, and Terek can drop by year 2015 by 5.6, 4.0, and 13.9%, respectively, and that of the Sulak can increase by 8–9% [15].

River Sediment Yield

Under natural conditions, the largest suspended sediment yield was recorded in the Kura (~35), Terek (~21), and Sulak (~15 million t/year), the fact that can be attributed to their runoff formation under mountain and semi-mountain conditions. The Volga yielded ~13 and the Ural, ~3 million t/year (Table 1).

Runoff regulation of the Caspian rivers caused a considerable drop in sediment yield into their deltas. The sediment yield at the river mouth dropped 1.5–1.8 times for the Volga, 1.3 times for the Terek, 8.6 times for the Sulak, and 2.5 times for the Kura (Table 1). The sediment yield of the Ural showed almost no changes. The long-term variations in annual sediment yield values generally follow the respective variations in river water runoff. However, an abrupt drop in sediment yield was recorded in the Kura since 1970 and, especially, in the Sulak since 1975 because of the effect of reservoirs and almost independent of variations in the current water runoff of the river.

Variations in Caspian Sea Level

The unstable water balance and large-scale sea level variations are the main features of Caspian Sea regime. Most geographers, climatologists hydrologists, oceanologists, and geomorphologists (beginning from E.Kh. Lents and A.I. Voeikov) believe the major cause of this to be of climatic, more exactly, water balance character [18, 22, 55, 56]. The major factors governing the Caspian water balance are the climate conditions in Volga basin and the water runoff of this river. Its variations caused the large-scale variations in sea level

Though a relationship between Caspian Sea level and Volga water runoff was mentioned by many

Table 2. Variations in Caspian Sea level H_s at Makhachkala gauge

Period (number of years)	H_s, m BS		Level variations	
	in the beginning of the period	in the end of the period	m	cm/year
1830–1882 (52)	–25.4	–25.1	+0.3	+0.6
1882–1900 (18)	–25.1	–25.57	–0.47	–2.6
1900–1929 (30)	–25.57	–25.88	–0.31	–1.0
1929–1941 (12)	–25.88	–27.84	–1.96	–16.3
1941–1977 (36)	–27.84	–29.01	–1.17	–3.3
1977–1995 (18)	–29.01	–26.66	+2.35	+13.1
1995–2010 (15)	–26.66	–27.30	–0.64	–4.3

researchers, no reliable estimate of this relationship has been established. Direct correlation between the mean annual values of sea level H_s and Volga discharge Q at Verkhnee Lebyazh'e gauge failed to yield a reliable dependence. The authors of this paper have used regression analysis to study the relationship between mean annual discharge H_s and the ordinates of curve of the accumulated normalized deviations of annual water discharges from their long-term mean of the Volga $\Sigma(K-1)$. Here, $K = Q_i/Q_0$, where Q_i are the current values of Q for each year, Q_0 is their average value for the period under consideration. Such curve is given in Fig. 2b.

The resulting regression equations are as follows: for the entire series (from 1929 to 1995), including data for the periods when sea level both was dropping and rising, $H_s = 1.0017\Sigma(K-1) - 26.75$ with the linear correlation coefficient $r = 0.864$; for the period when sea level was dropping (1929–1941), $H_s = 0.8127\Sigma(K-1) - 25.89$ at $r = 0.992$; for the period when sea level was rising (1977–1995) $H_s = 1.18667\Sigma(K-1) - 25.89$ at $r = 0.966$; for the period including years when sea level was dropping or rising (1929–1941, 1977–1995), $H_s = -0.666\Sigma(K-1) - 26.86$ at $r = 0.939$. The obtained regression equations show, first, that the Caspian level really depends on Volga runoff, though this dependence is not direct, but should allow for river water accumulation in the sea; second, that such dependence is most close in the period when sea level is dropping and somewhat less distinct for the period when sea level is rising and for the series combining both these periods; third, the explanation of this phenomenon requires the engagement of no hypotheses (e.g., geological ones used to account for large-scale variations in Caspian Sea level) other than water balance (Caspian Sea level is determined its water balance, whose major component is river runoff determined by climate conditions, primarily, in Volga basin). This is also supported by direct calculations of Caspian Sea water balance over individual periods with allowance made for all its inputs and outputs [18, 30].

Geomorphologists have carried out a number of large studies of variations in the sea level during Pleistocene (the latest 700–500 thousand years). These studies were based on the analysis of the stratigraphy of deposits and the positions of the ancient shorelines reflected on land surface and the sea bed [14, 22, 29, 53–56, 58]. The elevations of the ancient shoreline positions were converted to the present-day Baltic system (m BS). The studies mentioned above proved that Caspian Sea level varied within a wide range of >200 m: from –160 to +50 m BS (i.e., greater than World Ocean level). The highest level rise in the Caspian Sea took place during the Bakinskaya, Early Khazarskaya, and Early Khvalynian transgressions (the last-named dated at 30–13 thousand years ago, when sea level rose to 45–50 m BS), and the Enotaevskaya (13–11 thousand years ago) and Mangyshlakskaya (10–8 thousand years ago) regressions, when sea level dropped to –113 and –100 m BS, respectively.

In Holocene (the latest 10 thousand years) sea level showed wide variations. During several stages of the Novokaspian transgression, sea level rose to –19 or –15 m BS, while during the regressions separating those stages, sea level dropped to –30 or –39 m BS [22, 53]. In the historical time (the latest 2500–2000 years), Caspian Sea level varied from –35 to –25 m BS. In the II–I centuries BC, sea level stayed low (from –31 to –33 m BS). Since the beginning of the I century AD until the early V century, the elevations of sea level were close to their present day values (about –27 m BS). In the V–VI centuries, during the Derbent regression, sea level dropped to its lowest position over the historical time (–30 or even –35 m BS). The level was higher in the VII–X century, lower since the late X to the early XII century and higher again since the late XII to the early XIX century. The highest sea level in the historical time was recorded in the early XIX century (about –25 m BS) [54]. After that, a long period of level decline began.

Instrumental observations of Caspian Sea level began in the 1830s (data from Makhachkala gauge since 1900 are considered as the most reliable). Analysis of these data (Table 2, Fig. 2c) suggests the exist-

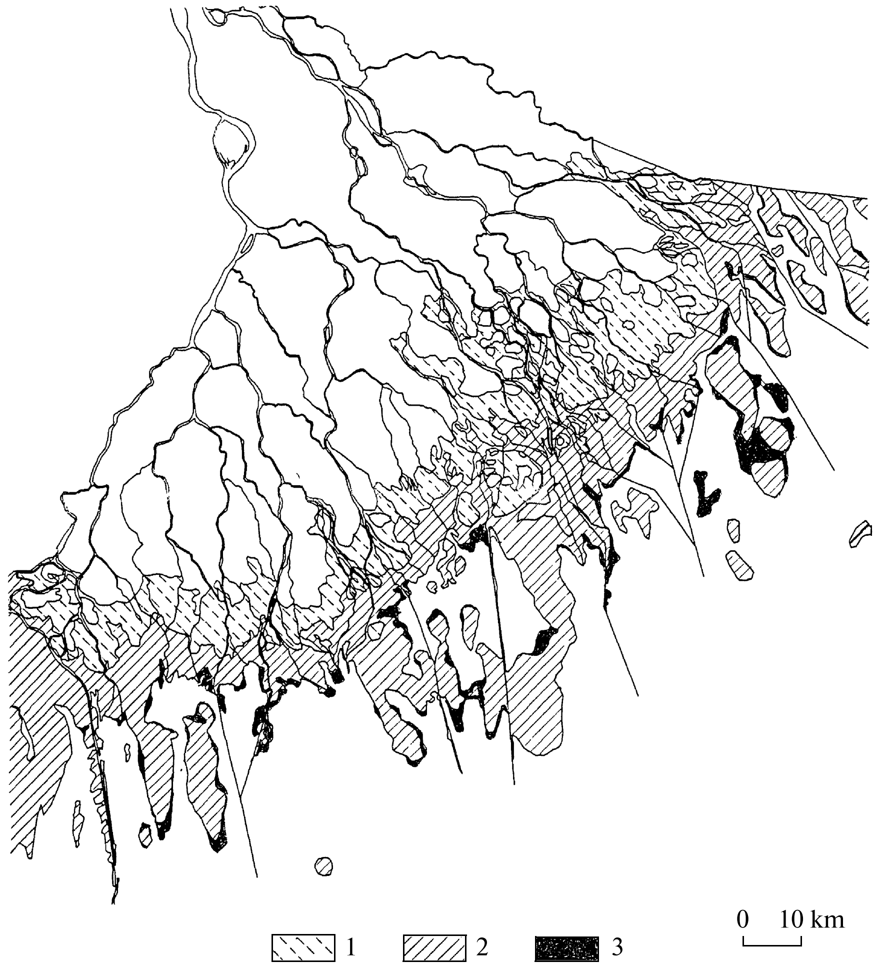


Fig. 3. Scheme of the Volga delta growth during (1) 1868–1927, (2) 1927–1976, (3) 1976–2000 after I.A. Labutina [47].

ence of five distinct periods in Caspian level variations in the XIX–early XXI century: a long and slow drop in sea level since the mid-XIX century to 1929 (from about –25.5 to –25.9 m BS), a rapid and considerable drop in 1929–1941 (by 1.9 m), a slow decrease in 1941–1977 (by 1.2 m), a rapid and considerable rise in 1977–1995 (by 2.3 m), and a relative stabilization in 1995–2010 with a slight trend toward a decrease.

Seasonal variations in the sea level are not wide. The storm surge variations in the level are most pronounced in the relatively shallow Northern Caspian sea and at the mouths of the Volga and Ural [18, 26, 30, 51, 61]. In the steep nearshore areas at the modern mouths of the Terek, Sulak, and Kura, the storm surge level variations are weak.

Wind Sea Waves

Winds of eastern direction dominate during a year in the nearshore areas of the Volga and Kizlyarskii Bay (the nearshore area of the Old Terek delta). The waves in the shallows in the Volga nearshore area and in Kizlyarskii Bay are weak. In all seasons, winds of western and eastern directions dominate at the Ural mouth.

Near the mouths of the Terek (the coastal zone of Agrakhanskii Peninsula) and the Sulak, southeastern and northwestern winds dominate, creating moderate waves with the same direction (their recurrence reaches 30 and 25%, respectively). The most hazardous are assumed to be waves with the southeastern direction. This determines the direction of alongshore drift of delta erosion products (from the south to the north along the shore) [17].

Strong northern and northeastern winds are often recorded near the Kura mouth. These winds cause waves with a northern component in Kura mouth area. The height of waves with 5% occurrence in the coastal zone reaches 3–4 m. These high waves cause a strong southward alongshore sediment drift [16].

Table 3. Characteristics of land accretion at the Volga mouth during 1927–1982 [52, 61]

Period (number of years)	Sea level, m BS, in the beginning (above line) and end of the period (below line)	Type of land accretion	Area increment		Linear incremen	
			km^2	km^2/year	km	km/year
1927–1937 (10)	–26.23 / –26.92	Deltaic	1100	110	5.8	0.58
		Insular	700	70	3.7	0.37
		Total	1800	180	9.5	0.95
1937–1960 (23)	–26.92 / –28.23	Deltaic	65	2.8	0.3	0.013
		Insular	490	21.3	2.6	0.11
		Total	555	24.1	2.9	0.13
1960–1982 (22)	–28.23 / –28.23	Deltaic	50	2.3	2.6	0.12
		Insular	0	0.0	0.0	0.0
		Total	50	2.3	2.6	0.12

CHANGES IN THE STRUCTURE AND REGIME OF THE VOLGA MOUTH

Large-scale variations in Caspian Sea level have always played the leading role in Volga mouth evolution. The position and size of the delta constantly varied, following the rise of drop in sea level. During sea transgressions, first a part of the old delta was inundated and next the entire delta and a higher part of Volga valley. The delta formation area shifted upstream. By contrast, during regressions, this place shifted downstream, the old delta or its upper part died, and the head of the new delta abruptly shifted seaward. When sea level was relatively stable, the delta increase was active, i.e., associated with the deposition of river sediments on the bed in nearshore area. During level drop, the increase in the delta became active–passive, where the role of the passive protrusion was the greater, the faster and larger was sea level drop and the more flat was the coastal zone of the sea. Of great importance in the increase in delta area during sea level drop were the relief of the nearshore area, the merging of former shallows and islands with the delta coastline, and the strong overgrowth of the nearshore area with aquatic plants.

During the Pliocene alone, the Volga changed its position within the distance of more than 2000 km: from Apsheronskii Peninsula (during the existence of Balakhanskoe Lake) to the present-day Kama mouth (during the Akchagylskaya transgression) [48]. No less than seven Volga deltas formed within Volga valley segment from the Kama mouth to the present-day sea shore in the Quaternary, not considering the ancient deltas whose signs can be seen on sea bed. The ancient deltas that formed during sea transgressions include, for example, the deltas of Bakinskoe time with heads near present-day Volgograd, Late Khazarskoe time with a head near Kamyshin, Early Khvalynian time with a head downstream of the Kama mouth, and Late Khvalynian time with a head at Chernyi Yar [48].

The best studied is the migration of the Volga mouth in the period of Early Khvalynian transgression, when Caspian Sea level rose to 50 m BS. Volga valley was inundated in that period, and the Volga mouth became a narrow water body of estuary–liman type with a length of 500–1000 km [22, 49, 57, 58]. According to some data [49], the backwater zone from the side of the sea propagated to the present-day Kazan. At levels above 20–24 m BS, the Caspian and Black seas formed a single water body [49, 55].

During large transgressions of the sea, Volga channel deeply incised into its own deposits [49]. Simultaneously, Volga DCL shifted far southward. At the present-day depths of the Caspian Sea of ~37 m (elevations of –64 m BS), signs of ancient common delta of the Volga, Ural, Kuma, Terek, and Sulak, which formed 17–22 thousand years ago during the deep Enotaevskaya regression [14], which apparently coincided with Valdai glaciations. Signs of the coastline of the joint delta of the Volga, Ural, Terek, and Sulak were also detected at present-day sea depths of ~23 m or at elevations of –50 m BS [14]. This delta existed during the Mangyshlak regression ~10 thousand years ago. Its coastline lied east of the present-day Agrakhanskii Peninsula [57].

The modern delta started forming in the Novokaspian time, i.e., about 8–7 thousand years ago, when sea level rose to –19 or –22 m BS. Its head first lied north of the head of the present-day delta (near the present-day Verkhnee Lebyazh'e Village); however, ~3500 thousand years ago, the delta shifted to its present place (Fig. 1a) and since then has not changed its position [10, 11]. In the "Chronicle of Old Times," written in 1118, it is mentioned that the Volga empties into the Caspian Sea with 70 mouths [10]. In year

Table 4. Elevations of mean annual water levels in the sea, H_s and at the delta coastline H_{DCL} and their differences ΔH

Year	H_s, m BS	H_{DCL}, m BS	$\Delta H = H_{DCL} - H_m$, m
1920	–26.10	–26.0	0.1
1930	–26.03	–25.8	0.2
1940	–27.76	–26.5	1.3
1950	–28.00	–26.6	1.4
1960	–28.23	–26.8	1.4
1970	–28.38	–26.9	1.5
1977	–29.01	–26.9	2.1
1980	–28.57	–26.8	1.8
1990	–27.59	–26.6	1.0
2000	–27.10	–26.5	0.6
2009	–27.21	–26.6	0.6

1546, the main delta branch was the one now referred to as the Old Volga [13].

Changes in the Structure and Regime of the Volga Mouth in the Period when Sea Level Was Dropping in the Recent 250 Years

Changes in the structure of the Volga delta in the XVIII–XX centuries have been studied by the analysis of schematic and topographic maps, and, recently, space survey data [3, 6–8, 11, 27, 30, 33, 36, 37, 41, 47, 51, 52, 57, 61, 65, 68]. Those papers characterize in detail the processes of delta protrusion into the sea, the development of its hydrographic network and the dynamics of Volga DCL. Without the reproduction of the content of those studies, we will consider only the major regularities in the Volga delta development in the period when sea level was dropping from the mid-XVIII to 1977, inclusive.

According to [6, 7], in the middle of the XVIII century, at relatively high sea level position at the Volga mouth, there existed three relatively isolated alluvial fans of the branches of Bakhtemir, Old Volga and Bolda, and Buzan. Three bays formed in the middle and eastern parts of the delta, but they disappeared by the 1870s. The delta protruded far into the sea only in the western part. In the XIX century, the main factor of delta protrusion was a considerable drop in sea level, rather than river sediment deposition. The process of delta progradation in that period is best illustrated by the schemes compiled by I.A. Labutina [27, 47] (Fig. 3) and the quantitative estimates given by M.M. Rogov [52] (Table 3).

In the XIX century, as sea level declined, vast islands—dried out shallow areas of nearshore bed—merged with the delta. For example, the huge Zyudevskaya Spit merged with the delta, hence the delta protruded here by 15 km at once. Later, the large Tishkovskaya spit merged with the delta [7]. Overall, the eastern part of the Volga delta was more rapidly protruding in the XIX century, and its central part, in the XX century.

According to [52] (Table 3), the greatest rate of delta protrusion was recorded in 1927–1937, when sea level dropped by ~0.7 m. In 1937–1960, when sea level dropped even greater (1.31 m); the increase in delta area was appreciably less. However, in 1960–1982, when sea level first dropped from –28.23 to –29.01 m BS (by 0.78 m) and next rose by the same value, the delta area practically did not change. As specially mentioned in [52, 61], after 1960, notwithstanding the level drop, which continued until 1978, the position of Volga DCL practically did not change.

The discordance between the changes in the Volga delta and the character of sea level drop in 1927–1982 has not been adequately explained in the scientific literature. The authors of [33, 47, 52, 61] supposed that the changes in delta area and DCL protrusion being discordant with sea level drop is due to the character of the emerging bed relief of the nearshore area. In this paper, we propose another explanation.

The cause of the distinct discordance between the increase in delta area and sea level changes is the disagreement between many-year variations in water level at Volga DCL (it is these variations that determine the displacement of the delta seashore) and sea level variations beyond the river mouth area (at Makhachkala gauge). Volga mouth area appears to be the only river mouth in the world, where water level at DCL (H_{DCL}) in some periods of river mouth development is not determined by sea level (H_s). As will be shown below, now $H_{DCL} \sim H_s$ at the mouths of all other rivers flowing into the Caspian Sea. As can be seen from Fig. 2 and data from [21], in the period of sea level drop until 1978 and during its rise in 1978–1995, water level near Volga DCL (between Iskusstvennyi Island gauge and Olya gauge) was higher than sea level. Estimates of the difference between those levels are given in Table 4. The difference $\Delta H = H_{DCL} - H_s$ was small in the period when sea level was high (1920–1930) (in other words, the level at DCL is almost the same as H_m). However, when sea level was abruptly dropping, ΔH was rapidly growing and reached 2.1 m in the year when sea level was the lowest (1977) [21]. This means that when sea level drops below the elevations from –26.5 to –27.5 m BS, the hydraulic relationship between delta streams and the sea breaks down and the further sea level drop has no effect on water level in the lower part of the delta. This unusual phenomenon is due to the existence in Volga mouth area of an extremely wide and shallow nearshore zone. When sea level drops below –26.5 m BS, the nearshore area, whose bed is the inundated surface of a more ancient river delta, starts functioning as a huge drowned weir with a broad crest. The specific features of the hydraulic interaction between the river and the sea at different H_s are schematized in Fig. 4.

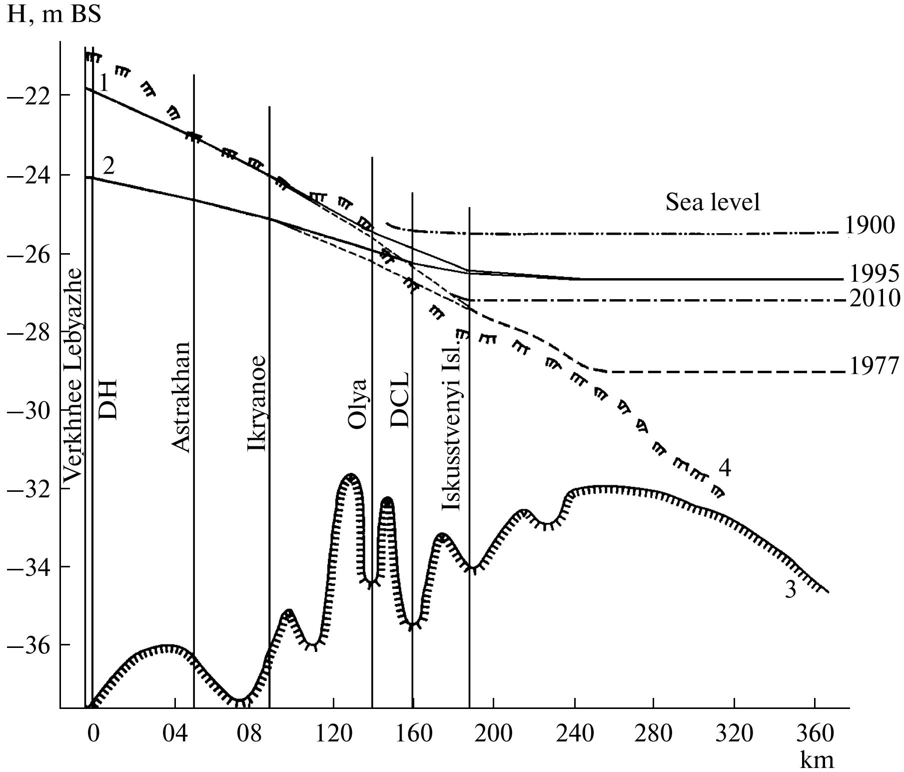


Fig. 4. Longitudinal profiles through Volga mouth area along the Bakhtemir Branch and Volga–Caspian Canal (VCC) according to [21, 36]: water surface at Volga water discharge of (1) 20 000 and (2) 8000 m^3/s and at sea level of (dashed line) 1977 and (full line) 1995; (3) VCC bed; (4) the surface of the delta and bed of the nearshore mouth area outside the canals. DH is delta head, DCL is delta coastline.

Data in Figs. 2c and 4 and in Table 4 show that in the XX century, the most considerable drop in water level near DCL was taking place in the 1920s–1950s (from –26.0 to –26.7 mBS), and it was the time when the delta was rapidly protruding into the sea. After 1960, the decline in H_{DCL} almost ceased, notwithstanding the still continuing rapid drop in H_s. This was the cause of the cessation in the Volga delta protrusion into the sea. Its passive protrusion contributed most to the increase in the Volga delta area in the XX century. This can also be seen from the fact that in 1960–1982 (Table 3), the heights H_s and H_{DCL} being practically constant, the delta increment was as little as 50 km^2 (2.3 km/year). It is possible, that those processes were affected by the appreciable decline in river sediment yield because of the construction of Volga–Kama multireservoir system (Table 1).

After 1950–1960, when delta protrusion into the sea first abruptly slowed down and next completely ceased, water level in the nearshore zone stabilized (Fig. 2c), but since H_s continued dropping, the width (in the seaward direction) of the shallow nearshore zone L_{nsh} started increasing. At high H_s (–26.5 m BS), the value of L_{nsh} was ~30 km, and it increased to 120 km by 1977 (Fig. 4).

Unlike other Caspian river mouths, sea level drop did not cause considerable erosion of branch channels. This is because at sea level drop, the river base level was not that level, but the surface of the bed in nearshore area and the level near DCL, which in the period of sea level drop never fell below –26.9 m BS (Table 4). As can be seen from Fig. 2c, sea level drop in 1920–1977 had practically no effect even in the lower reaches of the Bakhtemir branch (Olya gauge).

Sea level drop in the XX century has also almost no effect on the hydrological–morphological conditions in the Volga delta. The redistribution from 1951 to 2002 of water discharges between the major delta branches is not associated with changes in sea level. It is due to the regular (typical of all large deltas) processes of many-year concentration of runoff in major branches. Studies [21, 30, 41, 43, 51, 52, 61] showed that the intensification of flow through major branches (including their bifurcations near DCL) and the dying of smaller ones take place all over the extremely braided channel network in the Volga delta. The number of silting or dying watercourses in the Volga delta is much greater than that of that of eroded and becoming more active. The silting of such watercourses is not accompanied by the erosion of large branches. Therefore, the overall sediment balance in the Volga delta is appreciably negative. Not less than 30% of sediment

Table 5. Years of the beginning of water level rise and its maximal rise by 1995 at different gauges at the Volga mouth at different water discharges Q in delta head [21]

Gauge station (distance from DCL)	Q, m^3/s	Year when level rise began	The magnitude of level rise by 1995, m
Iskusstvennyi Island (–27)	8000	1981	0.9
	10000	1982	0.8
	16000	1983	0.7
	20000	1983	0.6
Olya (24)	8000	1988	0.4
	10000	1989	0.3
	16000	1990	0.2
	20000	1992	0.1
Ikryanoe (73)	8000	1993	0.1
	10000	1994	<0.1

yield in the river stays in the delta (either in dying branches and bypasses or on its surface).

The total number of streams reaching the Volga nearshore area depends on variations in water level at DCL. During the rapid delta protrusion into the sea in the first half of the XX century, the number of watercourses reaching the DCL decreased from 330 to 230 because of their merging (170 and 60 watercourses in the western and eastern parts of DCL, respectively) [7]. The number of branch mouths at DCL increased to 850 [10], when water level at DCL stabilized, and to 1000 in the 1980s [52]. New counts of branch mouths showed their number to decrease (maybe partly because of the overgrowth and silting of their mouths) [61]. The number of watercourse mouths was 300 in the western part of DCL and 200 in its eastern part.

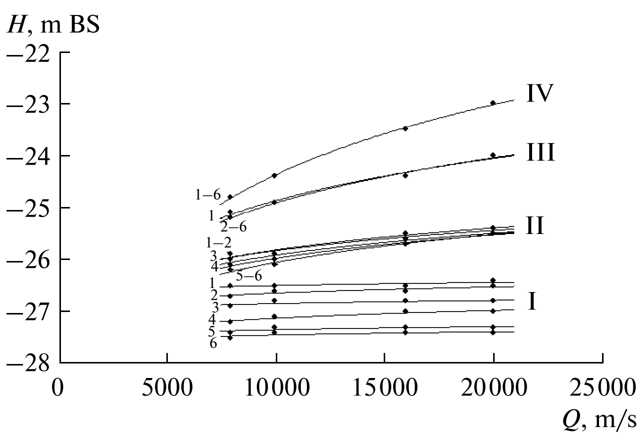


Fig. 5. Water levels at gauges in Volga mouth area (I) Iskusstvennyi Island, (II) Olya, (III) Ikryanoe, and (IV) Astrakhan vs. Volga water discharge at DH and sea level at Makhachkala gauging station of (1) –26.7, (2) –27.0, (3) –27.5, (4) –28.0, (5) –28.5, and (6) –29.0 m BS after [21].

Changes in the Structure and Regime of the Volga Mouth in the Period of Recent Rise and Subsequent Stabilization of Sea Level

The hydrological and morphological state of Volga mouth area in the period of sea level rise in 1978–1995 and during its subsequent relative stabilization is essentially different from those for other Caspian rivers in the same period.

The main feature of processes at the Volga mouth in the period of sea level rise was the gradual inundation of the nearshore area during such rise with a weak effect on delta regime. The rise of sea level and the gradual decrease of nearshore area width was the reverse process with respect to that accompanying the previous level drop and described above.

Water level rise at the offshore boundary of the nearshore area started simultaneously with level rise at Makhachkala gauge, i.e., since 1978. However, in the points nearer to Volga DCL, the beginning of level rise lagged appreciably behind that (Table 5). The process of gradual inundation of the shallow nearshore area is schematized in Fig. 4. The process of water level rise in the nearshore area near DCL (Iskusstvennyi Island) and at gauges in the Bakhtemir Branch are in good agreement with the plots $H_i = \varphi(Q_r, H_s)$ (Fig. 5). Figures 2c, 4, and Table 4 show that, at low river water discharge, the level rise at Volga DCL started approximately in 1983–1985. By 1995, the maximal level rise here was ~0.5 m. The backwater effect from the level rise extended from Volga DCL along the Bakhtemir branch (Fig. 4, Table 5), at low water discharges, slightly upstream of the Ikryanoe gauge, i.e., by ~80 km (it did not reach Astrakhan City).

Thus, contrary to the opinion of some researchers, the propagation distance of backwater effect into the Volga delta was not large even in the deep Bakhtemir Branch. The length of the backwater zone in the Buzan and Bol'shaya Bolda branches was as little as 40 and 30 km, respectively [21]. When water discharge in the Volga was large (>16000 m^3/s), the backwater zone in the Bakhtemir Branch did not exceeded 30 km. No significant sediment deposition in Volga delta branches was recorded in the period of sea level rise in 1978–1995.

As mentioned in the previous section, the position of Volga DCL has little changed since 1962. Such was the situation until the late 1980s. After water level near DCL started increasing, though slowly, some small changes took place along the marine part of the delta. For instance, DCL retreat was observed near the mouth of the Kizan (Kamyzyak) Branch and in some other areas [47]. According to data in [3], the total land area at the Volga mouth decreased by 875 km^2 in 1979–1998. This was mostly due to the inundation of some islands in the nearshore area. The decrease in land area was the largest in the western part of the delta (719 km^2). In its central and eastern parts, the position of DCL remained practically unchanged.

Table 6. Morphometric characteristics of the Ural delta (the length along the main channel L, the area F and its change ΔF from 1772 to 1996 according to [25, 26, 30, 36, 51]; figures in parentheses are approximate)

Year	H_s, m BS	L, km	F, km^2	Changes			
				ΔH_m		ΔF	
				cm	cm/year	km^2	km^2/year
1772	(–25.1)	4.0	30				
				–20	–0.32	50	0.81
1834	(–25.3)	10.0	80				
				–62	–2.21	23	0.82
1862	–25.92	13.1	103				
				–31	–0.48	132	2.03
1927	–26.23	19.1	235				
				–170	–9.44	128	7.11
1945	–27.93	22.3	373				
				–60	–3.53	119	7.00
1962	–28.53	30.0	492				
				–48	–3.20	30	2.00
1977	–29.01	32.0	522				
				221	11.63	–172	–9.05
1996	–26.80	32.0	(350)				

After 1995, when sea level reached its maximum, it first slightly dropped, next slightly rose, and dropped again. Overall, the sea level drop in 1995–2009 was 64 cm (Table 2). Those changes caused a level drop at DCL and Olya gauge (Figs. 2c, 5) by as little as 0.2–0.3 m. This could not cause any significant changes in the marine part of the delta.

The changes in the structure and regime of the Volga mouth in the nearest future will depend on sea level variations, which now cannot by predicted with confidence. In the case of a new considerable drop in sea level, the processes at the Volga mouth will follow the same scenario as during the level drop in the first half of the XX century, as mentioned above. if a considerable new level rise takes place, a significant retreat of DCL can be expected only at sea level above –25.5 m BS: at the level of –25.0, a strip of land along DCL with a width of up to 15–20 km in the west and 40–45 km in the east of the delta will be inundated. At sea level of –23 m BS, the major portion of the delta will be inundated and its natural complex will degrade heavily [30].

CHANGES IN THE STRUCTURE AND REGIME OF THE URAL MOUTH

The Ural Mouth in the Geological Past

The migration of the Ural mouth over Prikaspiiskaya Lowland, as well as that for the Volga mouth, has been always controlled mostly by sea level variations. Changes in the Ural delta position are best known for the period since the Early Khvalynian transgression of the Caspian Sea [25, 26].

In the Khvalynian and Novokaspian times, in periods of relative stabilization of Caspian Sea level, at least seven deltas, including the present one, formed in the lower reaches of the Ural River [25]. The ancient deltas of the Ural in its present-day lower reaches include three deltas of the Early Khvalynian time: a nameless delta (shoreline elevation of 50 m BS) and the Kushumskaya (20 m) and Mergenevskaya (0 m BS) deltas. The Bogariiskaya (0 m) and Sortasskaya (–16 m BS) deltas formed in Late Khvalynian time [25, 26, 30, 36].

Changes in the Present-Day Ural Delta and Its Regime

The formation of the present-day Ural Delta started apparently in the mid-XVIII century. The development of the delta since that moment and up to now has been documented by topographic maps and, recently, space photographs [25, 26, 30, 36, 51].

The general trend in the development of the present-day Ural delta in the period of the latest sea level drop, i.e., until 1977, shows, first, its rapid protrusion into the sea (Fig. 6) and an increase in its size (Table 6), and, second, the formation of 1–3 large longitudinal branches and small lateral ephemeral bypasses. The delta protrusion into the sea in this period, which was mostly due to sea level drop, was largely passive, since sediment yield in the Ural is

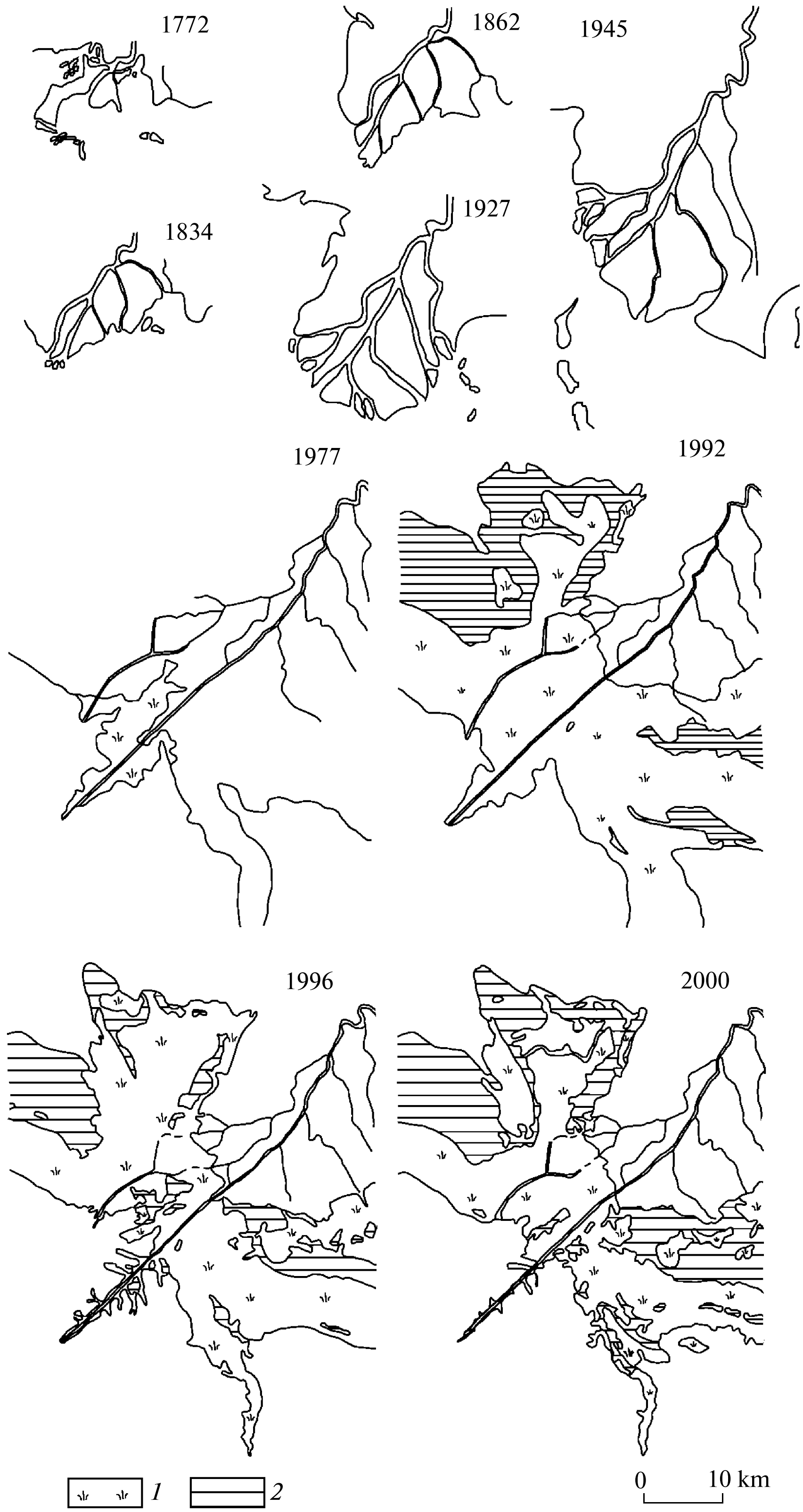


Fig. 6. Changes in the Ural delta from 1772 to 2000 after [26, 36, 51]. (*1*) Reed cover, (*2*) open water after sea level rise, separated from the sea by reed belts.

small. Changes in water level in the Ural delta and its mouth area during sea level variations significantly differed from the analogous changes at the Volga mouth considered above. Ural nearshore area is not as vast and shallow as that of the Volga. Therefore, both drop and rise of sea level in the XX century rapidly propagated into the delta and the mouth area of the Ural. For example, the abrupt drop in sea level in 1929–1940 by almost 1.8 m caused an almost simultaneous level drop at Gur'ev (now Atyrau) gauge by 1.6 m [51]. The decrease in water level was accompanied by an increase in the slope of water surface, bottom erosion, and gradual incision of the channel. At Topoli gauge (172 km upstream of Gur'ev gauge), the level drop manifested itself only in 1942, i.e., 10–12 years after the start of the drop, and reached ~1.2 m by 1951. The propagation rate of the backward erosion was ~20 km/year [51]. The sea level drop in the 1970s by ~0.7 m led to a drop in water level at Gur'ev gauge by ~0.2 during spring flood and ~0.5 m in dry season. The total propagation distance of the effect of sea level drop in the XX century was not less than 300 km [51].

The 2.2-m level rise in 1978–1994 caused a rise of water level at Atyrtau gauge by 0.5 m during spring flood and 1.7 m during dry period [51]. The rise of level was especially significant after 1986. At Makhambet gauge (118 km upstream of Atyrtau gauge and 164 km from DCL), the backwater effect from the sea became evident since 1991 [51]. The length of the backwater zone caused by sea level rise by 2.35 m in 1978–1995 was not less than 230 km.

Starting from the mid-XVIII century, the Ural delta was protruding as a typical beak-type delta (Fig. 6). Since the late XVIII, when the left Peretaska bypass formed 6.2 km downstream of Gur'ev Town, this place is regarded as Ural DCL. In the early XIX century, the main channel of the Ural within the delta separated into two longitudinal branches—the right, Zolotoi Branch, and the left, Yaitskii Branch (Yaik). By the early XX century, the Yaitskii Branch has separated into the branches of the Left Yaitskii and the Right Yaitskii. In the second half of the XX century, a bypass (now referred to as the Damba) separated from the Left Yaitskii Branch, connecting it with the Zolotoi Branch. The continuation of the Zolotoi Branch was deepened for navigation and transformed into UCC, and the continuation of the Left Yaitskii Branch (Shman-Uzek bypass) was also deepened and transformed into a special fish pass, which runs parallel to the UCC to the nearshore area (Fig. 6). As the Ural delta protruded into the sea, the bypasses of Bukharka, Zaroslyi, and Zolotenok successively separated from the Zolotoi Branch to the left. They can be most clearly seen in maps of 1927 and 1945 (Fig. 6). Later, by 1977, all they have died. The large Peshnoi Island has merged with the delta by 1977, forming a peninsula.

Analysis of data in Table 6 shows that the increase in the Ural delta F until 1977 was taking place parallel to a drop in Caspian Sea level H_s. Regression analysis showed a close inverse correlation between F and H_s: $F = -123.35H_s - 3038$ at high correlation coefficient (–0.9735). To isolate the contributions of the passive and active protrusion of the delta, also found was the dependence between the rate of changes in delta area $+F$ and the appropriate rate of sea level change $\Delta F = -0.7984\, \Delta H_s + 0.6725$ also with a high correlation coefficient (–0.9445). This dependence shows that at $\Delta H_s = 0$, the rate of changes in delta area, not related with sea level change, was +0.672 km^2/year. This is the average rate of delta active protrusion into the sea because of river sediment deposition. The rate of active delta protrusion is much less than the rate of actual increase in Ural delta area at all stages of its evolution since the beginning of sea level rise in 1978 (Table 6). The actual rate of delta increase approached the mean rate of its increase of 0.672 km^2/year only in the initial period of delta development (0.81–0.82 km^2/year). Later, until 1977, the actual rate of delta area increase varied from 2 to 7 km^2/year (Table 6).

The sea level rise in 1978–1995 caused the inundation of the major portion of the Ural delta (Fig. 6, Table 6). The rise of sea level by 1992 caused the inundation of the near-sea delta zone 15 km in width east of the UCC and 30 km in width west of it. Peshnoi Peninsula again became an island. The near-sea part of the delta turned into reedy flooded areas, separated by open-water areas (lagoon-type water bodies). In 1992–1995, during the further rise of sea level, the nearshore reed belt was deteriorating and narrowing. Some branches, which had not been functioning before, were inundated (their channels were watered), and their runoff partially recovered.

CHANGES IN THE STRUCTURE AND REGIME OF THE TEREK MOUTH

The History of Terek Mouth Evolution until the XX Century

The strongest effect on changes at Terek mouth structure in the past was due to, first, large-scale variations in Caspian Sea level and, second, jump-like changes in the hydrographic network of the delta caused by large river sediment yield.

During sea regressions, the Terek delta protruded far into the sea, while during sea transgressions, the delta was inundated by sea water and the DCL retreated. Signs of ancient coastlines of Terek delta can be seen on the surface of the present-day delta and on seabed [14, 22]. Against the background of a generally decreasing sea level, in the latest 8–9 thousand years, depressions in the ancient-delta plain of the Terek were filling with river sediments. This process, as well as that at the mouths of some other rivers with large sediment yield (e.g., Amudarya, Huanghe, Ili, Mississippi), manifested itself in the cyclic formation of breakings and particular deltas [31].

The specific features of the Terek delta development in the recent 500 years, i.e., during the fifth stage of Novokaspian transgression can be seen in numerous historical and cartographic documents [9, 12, 17, 30, 37]. The dynamics of the Terek delta in this period essentially differed from the evolution of the Volga and Ural deltas described in previous sections. The difference consists in that the leading role in the process of the Terek delta protrusion in the historical time belonged not to sea level drop but to cyclic processes of delta development, which manifested themselves in periodical jump-like alternation in river runoff direction within Terek delta plain. This took place after the river broke through either along a shortest path toward the sea or into the lower part of the old delta.

The large number of channel breakings, including repeated in the same place, and the unreliability of old maps allow us to give only an approximate description of the development history of hydrographic network in the Terek delta until the early XX century. In the past 500 years, eight large transformations took place in the channel network in the Terek delta during eight delta formation cycles. Those cycles, which began form a large breaking of river or branch water in a new direction, received their names in accordance with the name of the main channel that formed during the given cycle.

Until XVI, the main runoff of the river reached the sea in eastward direction through a branch, whose old name is unknown. Since the late XVIII, this channel, which became active again, is referred to as Old Terek [12]. The breakings that followed initiated delta formation cycles, which received the names as follows.

Kuru–Terechnyi (XVI century). The main branch Kuru-Terek ran from the present-day Kizlyar Town northward toward Bryanskaya Spit in Kizlyarskii Bay, the Caspian Sea [12].

Sulu-Chubutlinskii and Kuru-Chubutlinskii (XVII century). The main branch of Sulu-Chubutla broke through toward the sea west from the Kuru-Terek Branch. Somewhat later, the Kury-Chubutla Branch formed parallel to the Sulu-Chubutla Branch east of it [9, 12]. By now, these branches have practically dried up.

Staroterechnyi (the early XVIII century). After a breaking, river water started moving eastward into the channel system, which is now referred to as the Old Terek. Only this branch is shown in the Terek delta in the map of 1725 [9].

Novoterechnyi (the late XVIII century). After a breaking through the right bank of a branch, which, apparently, has been called the Old Terek since then, a new powerful Kordonka Branch formed. This branch emptied into the middle part of Agrakhanskii Bay; this bay with the adjacent zone of flooded areas was named Novoterechnaya area. The Kordonka Branch is shown as a major one in the Terek delta on maps of the late XVIII century [9].

Borodzinskii (the early XIX century). After channel breaking in 1812 west of Kizlyar Town, a new northward branch Borozdinskaya Prorva formed [9]. However, it did not exist for long.

Talovskii (the mid-XIX century). The Talovka Branch formed after a breaking in 1847.

New Borodzinskii (the second half of the XIX century). A catastrophic breaking took place during a flood in July 1863 near Dubrovskaya Cossack village (because of which it was named Dubrovskii breaking. River water rushed northward toward Borozdinovskaya Cossack village, resulting in the resumption of water flow through the Borozdinovskaya Prorva branch. This breaking led to the inundation of 770 km^2 of land [9]. It also caused partial drying of the Old Terek and Talovka branches. However, later the new Borozdinovskaya channel system practically died and the flow through the Talovka Branch has resumed by 1904 [9].

Kargalinskii, which started in 1914 and continues at present.

All those delta formation cycles involved similar processes and included similar stages: a breaking and the formation of vast floods, flooded areas, and lakes; the formation of a multi-branch, first, overlapping particular delta (developing on the surface of an old delta) and later overlapping-adjacent delta (including a bay-filling delta or a delta of protrusion into the nearshore zone); the formation of a overlapping-adjacent particular delta with a few branches; the dying of this delta after a new breaking. The only exception is the latest cycle, which is not completed because of artificial engineering stabilization measures.

Nowadays, the remains of some branches (Sulu-Chubutla, Talovka, Old Terek, etc.) can be seen in the Terek delta only as artificially deepened and watered canalized channels.

Changes in the Structure and Regime of the Terek Delta during the Present Karaginskii Cycle of Its Development

The development of the Terek delta after 1914 is well known and can serve as a good example illustrating the cyclic processes in a river delta with a large sediment yield [2, 4, 9, 12, 17, 30, 36]. The Kargalinskii cycle of the Terek delta development includes four stages:

1914–1939. The breaking and formation of vast lakes and flooded areas as the result of inundation of the old delta;

1940–1962. The formation of multibranch overlapping and next, overlapping-adjacent delta;

1963–1977. The formation of an overlapping-adjacent delta with a few branches;

1977–present time. The formation of a protrusion delta in an open nearshore area in the Middle Caspian Sea.

Table 7. Morphometric characteristics of the particular deltas at the Terek mouth (their length along main branch *L* and area *F*) during the Karagalinskiy cycle of delta formation

Particular delta	Year	Sea level, H_s, m BS	L, km	F, km^2
Alikazgan	1939	–27.55	0	0
	1940	–27.76	0.6	–
	1948	–27.75	4.5	–
	1953	–28.26	8.0	46
	1956	–28.40	9.0	–
	1962	–28.53	12.0	68
	1967	–28.37	14.0	78
	1970	–28.38	18.0	86
	1973	–28.66	23.0	106
	1977	–29.01	32.0	130
New	1973	–28.66	0.67	1.03
	1977	–29.01	0.64	1.35
	1980	–28.57	1.23	2.52
	1982	–28.23	1.25	2.64
	1987	–27.81	1.40	3.16
	1991	–27.26	2.0	5.0
	1997	–26.95	2.2	7.5
	2003	–27.11	2.3	9.0
	2008	–27.14	2.7	10.5

I stage (1914–1939). Until June 1914, the major runoff of the Terek within its delta plain flowed northward through the Talovka Branch [9]. The new cycle of delta formation at the Terek mouth began with a breaking of river water from Terek channel near Kargalinskaya Cossack village during the catastrophic flood in June 1914. The breaking was provoked by an artificial discharge of flood water though the small Kargalinka bypass, carried out with the aim to prevent inundation in the upper part of the delta. River water rapidly scoured the channel of the bypass, which in the late 1914 intercepted 70–80% of Terek runoff [17]. River water rushed into the lower southeastern part of the old deltaic plain, where it caused a high inundation over an area of 740 km^2 [17]. Vast flooded areas and lakes formed in this part of the delta. By the late 1930s, ~100% of water entered the Kargalinskii gap during dry period and 90–97% entered it during spring flood. During the I stage, almost all transit sediments and the products of erosion of lake-separating ridges deposited in the lakes and flooded areas of the delta [2, 4, 17]. Terek water, leaving its sediments in flooded areas and lakes, entered Agrakhanskii Bay, which then had a passage toward Kizlyarskii Bay of the Caspian Sea and had water surface elevation slightly above the sea level. By the end of this stage, the major portion of river water runoff entered Agrakhanskii Bay through the Alikazgan bypass, which has existed here before. As the result of the interception of the major portion of river water runoff by the new gap, almost all the delta area developed for agriculture was deprived of water. Therefore, measures were taken in the 1930s with the aim to supply river water to this area. The Delta Canal was constructed in 1936, considerably straightening the Old Terek Branch, and a check sluice was constructed on the Terek in 1939 for water supply to the Delta Canal.

II stage (1940–1962). In this period, the major portion of flooded areas and lakes was filled with river sediments, and a multibranch network of a overlapping delta with a main branch called the Kargalinskii Proryv (sometimes referred to as the New Terek Branch [9]) started forming over them. An adjacent bay-head delta (the Alikazgan delta) started forming in

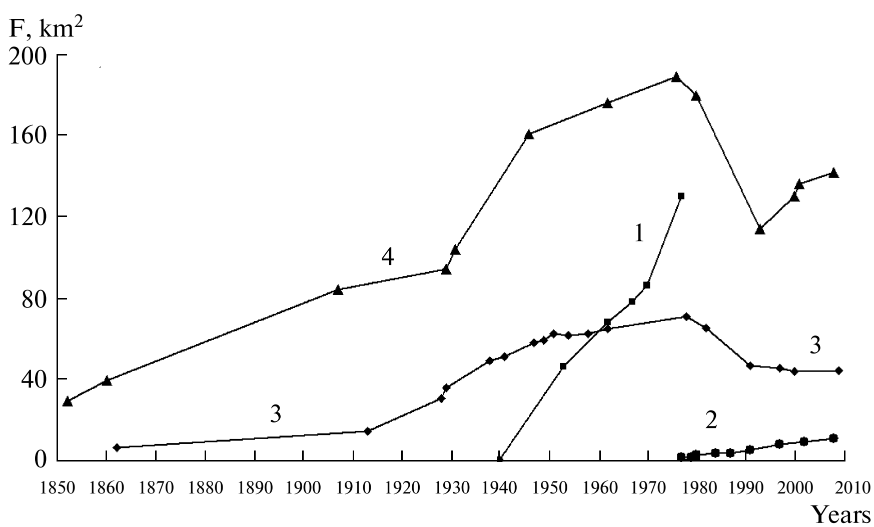


Fig. 7. Changes in the areas of the particular (1) Alikazgan and (2) the New Delta at the Terek mouth and (3) the Sulak and (4) Kura deltas.

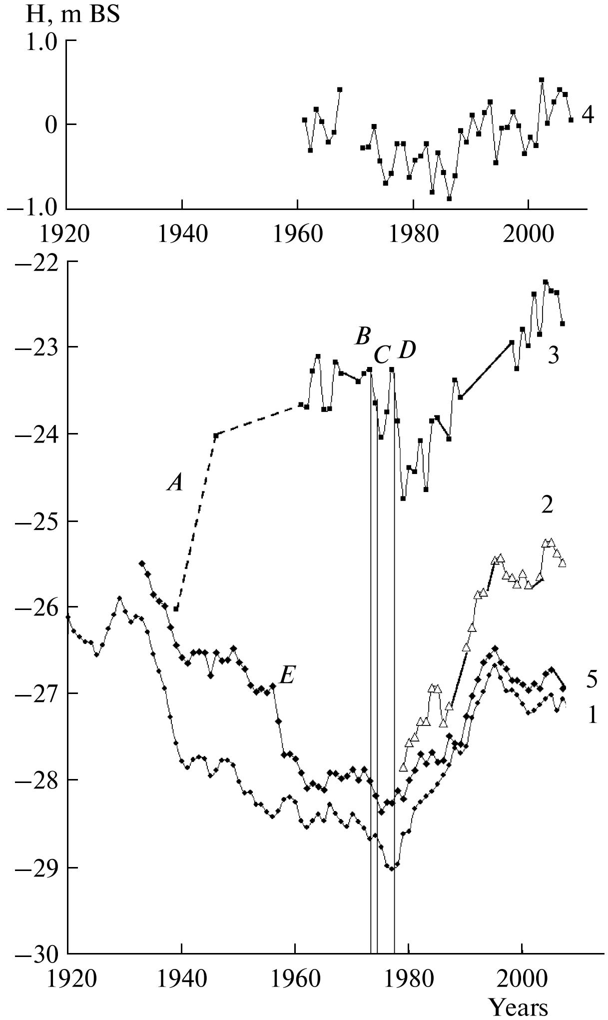


Fig. 8. Changes in annual water levels at (1) Makhachkala marine gauge, at the gauges of (2) Damba, (3) Alikazgan, (4) alter bay of the Kargalinskaya dam in the Terek delta and (5) Sulak gauge in the Sulak delta. (*A*) The period of the fast progradation of the Alikazgan delta into Agrakhan Bay, (*B*) the moment of coffer-dam breaking in the upper part of the cutoff in the early 1973, (*C*) the moment of cutoff closing in the late 1973, (*D*) the moment of new opening of the cutoff in the late 1977, (*E*) the moment of the artificial output of the Sulak waters into the sea in the new direction in the late 1957.

Agrakhanskii Bay. The beginning of the formation of this delta can be assumed to coincide with the first input of sediments into the bay in 1940 [12].

The percentage of river sediment yield entering the bay was first small, but later it started to gradually increase [2, 4, 17]. However, even a small amount of sediments was enough for the formation of a mouth bar of the placer type at the mouth of the Alikazgan Branch [12]. The division of the channel into branches began since 1943. By the 1948, the delta has protruded into the bay by 4–5 km [12]. The head of the Alikazgan delta was the site of separation of Alikazgan bypass as the continuation of the Kargalinskii Proryv branch into branches near the western bank of Agrakhanskii Bay 6 km downstream of Alikazgan gauge. The central channel (Main Branch) formed here as the continuation of the Kargalinskii Proryv Branch, and the left branch (Kubyakinskii Branch) and the right branches (Kuni Branch and Batmaklinskii Branch) also formed. By 1956, Main Branch channel, protruding by 9 km, approached the eastern shore of the bay, and the Alikazgan delta divided Agrakhanskii Bay into two parts—the Northern Agrakhan and the Southern Agrakhan [9]. Sediment deposition in the bay continued northward and by 1962, the delta elongated by 3 km and reached the total length of 12 km and area of 68 km^2)(Table 7). Two parallel continuations of the Main Branch formed in it—the Middle Branch and the Northern Branch.

The protrusion rate of the Alikazgan delta into the Northern Agrakhan gradually increased, favored by (Table 7, Fig. 7), first, the small depth of the bay and, second, the gradually increasing share of Terek sediment yield entering this part of river mouth [2, 17]. The annual rates of elongation of the main channel of the Alikazgan delta and the increase in its area at the end of the II stage of delta formation (1953–1962) reached the average values of 444 m/year and 2.4 km^2/year, respectively.

In the period under consideration, it was found that the measures for water supply to agricultural regions in the delta taken in the second half of the 1930s were insufficient. Therefore, additional hydroengineering operations were carried out [12] (Fig. 1c). In 1955, the Novoterechnyi Canal was constructed from the Delta Canal toward the Kordonka Canal. The entire system in this part of the delta was called the Novoterechnaya Irrigation System. In 1956, the Kargalinskii Hydroengineering Complex was constructed, including a low-head dam (the normal head of 1.05 m) and a check sluice on Delta Canal. In 1958, the Kopaiskii Hydroengineering Complex was constructed for water supply to the canalized channels of Borozdinskaya Prorva, Talovka, and Old Terek.

III stage (1963–1977). In this period, lateral branches were dying in both adjacent and overlapping deltas and runoff concentrated in a limited number of largest branches. The channel of the Kargalinskii Proryv branch from Kargalinskaya Dam to Agrakhanskii Bay took its shape. The lateral branches in the Alikazgan delta practically died. The runoff concentrated in the Main Branch, as a continuation of the Kagarlinskii Proryv branch.

The protrusion of the Alikazgan delta into the Northern Agrakhan continued with an increasing rate (Table 7). After 1962, the length of the Alikazgan delta increased by 20 km (from 12 to 32 km); and its area, by 62 km^2 (from 68 to 130 km^2). In 1962–1973, the elongation rate of the main channel in the Alikazgan delta was 1.0 km/year, while in 1973–1977, it was 2.25 km/year. The rate of delta area increase in the

Table 8. Changes in mean annual water levels at gauges of Alikazgan, H_A, and Makhachkala, H_M, water surface slopes and channel lengths L in the Alikazgan–sea reach during the III and IV stages of the Kargalinskii cycle of delta formation

Yea	Level elevation, m BS		Level fall, m	Channel length L, m	Slope, 10^{-5}	Changes	
	H_A	H_M				ΔL, km	ΔH_m, m
1962	–23.6	–28.5	4.9	18	27.2		
						12	–0.2
1973*	–23.3	–28.7	5.4	30	18.0		
						–10.0	0
1973**	–23.3	–28.7	5.4	20	27.0		
						10	0
1973***	–23.3	–28.7	5.4	30	18.0		
						7	–0.3
1976	–24.0	–29.0	5.0	37	13.5		
						1	0
1977****	–23.3	–29.0	5.7	38	15.0		
						–17.5	0
1977*****	–23.3	–29.0	5.7	20.5	27.8		
						0.7	0.6
1979–1982	–24.7	–28.4	3.7	21.2	17.4		
						0.9	1.7
1995	–23.0	–26.7	3.7	22.1	16.7		
						0.1	–0.5
2003	–22.3	–27.2	4.9	22.2	22.1		
						0.5	0.1
2008	–22.7	–27.1	4.4	22.7	19.4		

Notes: * before the breaking of the coffer-dam in the upper part of the cutoff;
** just after the breaking of the coffer-dam in the upper part of the cutoff;
*** after closing the cutoff;
**** before the new opening the cutoff;
***** just after the new opening the cutoff.

same periods was 3.45 and 6.0 km^2/year, respectively. The rate of delta elongation >1km/year is a rare phenomenon in river mouths. Such values have been recorded only for dynamics deltas, such as those of the Amydarya and Huanghe [31]. The acceleration of Aligazgan delta protrusion into Agrakhanskii Bay is due to the further increase in the share of Terek sediments entering Agrakhanskii Bay. in 1963–1977, this share increased to 55% (it was 44% in the previous period) [2, 17]. The small depth of the basin, which became even less because of level drop, also contributed to this process.

The rapid elongation of the channel in the process of Alikazgan delta protrusion into Agrakhanskii Bay caused a considerable drop in both the level differential between Alikazgan gauge and the sea and the water surface slope I (Table 8). This slope was 27.2×10^{-5} in 1962, while it has dropped to 18×10^{-5} by 1973. The decrease in I has led to the inequality $I < I_0$, where I_0 is the so-called stable slope, at which there are no significant vertical deformations. The slope I_0 for mean annual water runoff and sediment yield values for the lower reach of the Kargalinskii Proryv lies between 20×10^{-5} and 22×10^{-5} [17]. As the result, the transportation competency of the flow in the channel reach under consideration cannot fully ensure the transit of Terek sediments. To restore the relationship $I \sim I_0$, it was required to raise the elevations of both the bed and water surface throughout the lower reach of the Kargalinskii Proryv branch (Fig. 8). Thus, the large-scale accumulation of sediments in the channel took place despite the drop in sea level (Table 8, Fig. 8). Water level rise at Alikazgan gauge has began as long ago as before 1962 (Fig. 8). For example, it increased by ~2 m in 1939–1947 [12] and by 0.6 m more in 1947–1962. The backwater effect from the rising level propagated upstream of the Kargalinskii Proryv branch, creating the hazard of not only common inundation of lands during spring flood and freshets, but also a new breaking. Therefore, with the aim to prevent a catastrophic flood, a reserve canal ~5 km in length was dug through Agrakhanskii Peninsula [9, 17]; this canal was designed for the discharge of flood water directly into the Southern Caspian Sea in case of a high flood, thus preventing the inundation of the entire Terek delta. When finished, the canal was temporary blocked by an earth dam in its head, i.e., near the exit from the Main Branch in this area.

The continuation of the III stage of delta development at the mouth of the Kargalinskii Proryv Branch was unexpectedly ceased on January 3, 1973, when the upper dam of the reserve canal was broken and river water rushed eastward through the canal directly into the sea. Because of this, the length of the channel from Alikazgan gauge to the sea abruptly decreased from 30 to 20 km (Table 8) (this comprises the distance of 15 km from Alikazgan gauge to the reserve canal and the length of the canal itself of 5 km). The 10-km decrease in the channel length abruptly increased both the slope of water surface to 27.2×10^{-5} (Table 8) and the flow velocities and caused (at $I \gg I_0$) very strong erosion in the channel reach upstream of the reserve canal. The backward erosion zone started propagating upstream the river covering 20–30 km, and level drop at Alikazgan gauge by the end of 1973 was 0.3–0.4 m [17, 38].

The transit river sediments and products of erosion of the lower part of Kargalinskii Proryv Branch formed during 1973 a bar shallow at the mouth of the reserve canal and the signs of formation of a small particular adjacent protrusion delta appeared at the open sea coast; this delta was later called the New Delta of the Terek. By October 1973, longitudinal mouth spits and midstream sandbanks have formed in this delta by October 1973. The length and the area of this delta by the late October 1973 was 0.67 km and 1.03 km^2, respectively (Table 7). The development history of the New Delta of the Terek is described in detail in [1, 17, 36, 44]. The strong erosion in the channel of the lower reaches of the Kargalinskii Proryv Branch caused the drying of the northern part of Kargalinskii Bay and a considerable damage to fishery. Therefore, at the suit of fishery organizations, on October 31, 1973, the reserve canal was dammed, water flow into the Northern Agrakhan resumed, and the northward protrusion of the Alikazgan delta continued. Its length again reached 23 km; by 1977, it has increased to 32 km (Table 7). Simultaneously (under the recovery of the ratio $I < I_0$) the erosion in the channel downstream of Alikazgan gauge gave place to sediment deposition, and the channel in this segment has rapidly resumed the state it had before 1973. The rise in the elevation and level of water (Fig. 8) and bed continued. At the same time, the inundation hazard, which existed in the two previous decades, appeared again.

The New Delta of the Terek, deprived of water and river sediments, experienced wave impact, and has radically transformed since the late 1973 to August 1977. A barrier bar (a wave-cut bar) formed at its coastline and started slowly moving toward the shore and elongating along it. By the mid-1973, delta length slightly decreased (from 0.67 to 0.64 km) and its area, conversely, slightly increased because of the merging with the delta of marine accumulative forms (from 1.03 to 1.35 km^2) (Table 7). The history of transformation of mouth alluvial fan in the absence of river runoff is of particular scientific interest, it was described in detail in [17, 36].

IV stage (1977–present time). Considering the increasing hazard of strong floods, at the suit of water management organizations, a decision was made to reopen the reserve canal through Agrakhanskii Peninsula. The canal was opened on August 11, 1977, opening a new stage in delta formation at the mouth of the Kargalinskii Proryv Branch, this stage continuing now. The torrent of Terek water, rushing through the canal broke a barrier bar at the periphery of the "dead" delta at the reserve-canal mouth, thus restarting the development of the New Delta of the Terek (Fig. 9, Table 7).

The opening of the reserve canal in August 1977 disturbed the natural course of delta formation processes at the Terek mouth, which was interrupted for a short time in 1973. The deep incision of the channel and a considerable water level drop caused by the opening of the canal resulted in the stabilization of the Kargalinskii Proryv Branch, thus, maybe, preventing a new large restructuring of the hydrographic network within Terek mouth area. The anthropogenic stabilization of the Kargalinskii Proryv Branch was also facilitated by the recent large-scale operations for the modernization of old and the construction of new protection dikes. However, failures in the protection dikes took place in the Kargalinskii Proryv Branch, leading to local floods, e.g., in 2002, when large volumes of water entered in the zone of the former Kordonka Branch, and in 2005. Such breaks were promptly eliminated by diking, thus preserving the relative stability of the Kargalinskii Proryv Branch. Otherwise, such breaks could launch a large-scale restructuring of the hydrographic network throughout the Terek delta. Thus, the development of the Terek delta since the autumn of 1977 can be regarded as almost fully artificially regulated.

By the character of channel processes, the IV stage of delta formation can be divided into three intervals: (IVa) a very strong erosion in the channel of the Kargalinskii Proryv Branch, caused by a considerable decrease in channel depth because of the opening of the reserve canal against the background of very low sea level; (IVb) accumulation of sediments in the channel caused by an abrupt rise in sea level; (IVc) weak channel erosion, caused by a small drop in sea level.

During the interval IVa ((1977–1982), channel erosion and water level drop extended over the entire Kargalinskii Proryv Branch. The discharge into the sea of transit river sediments and erosion products accel-

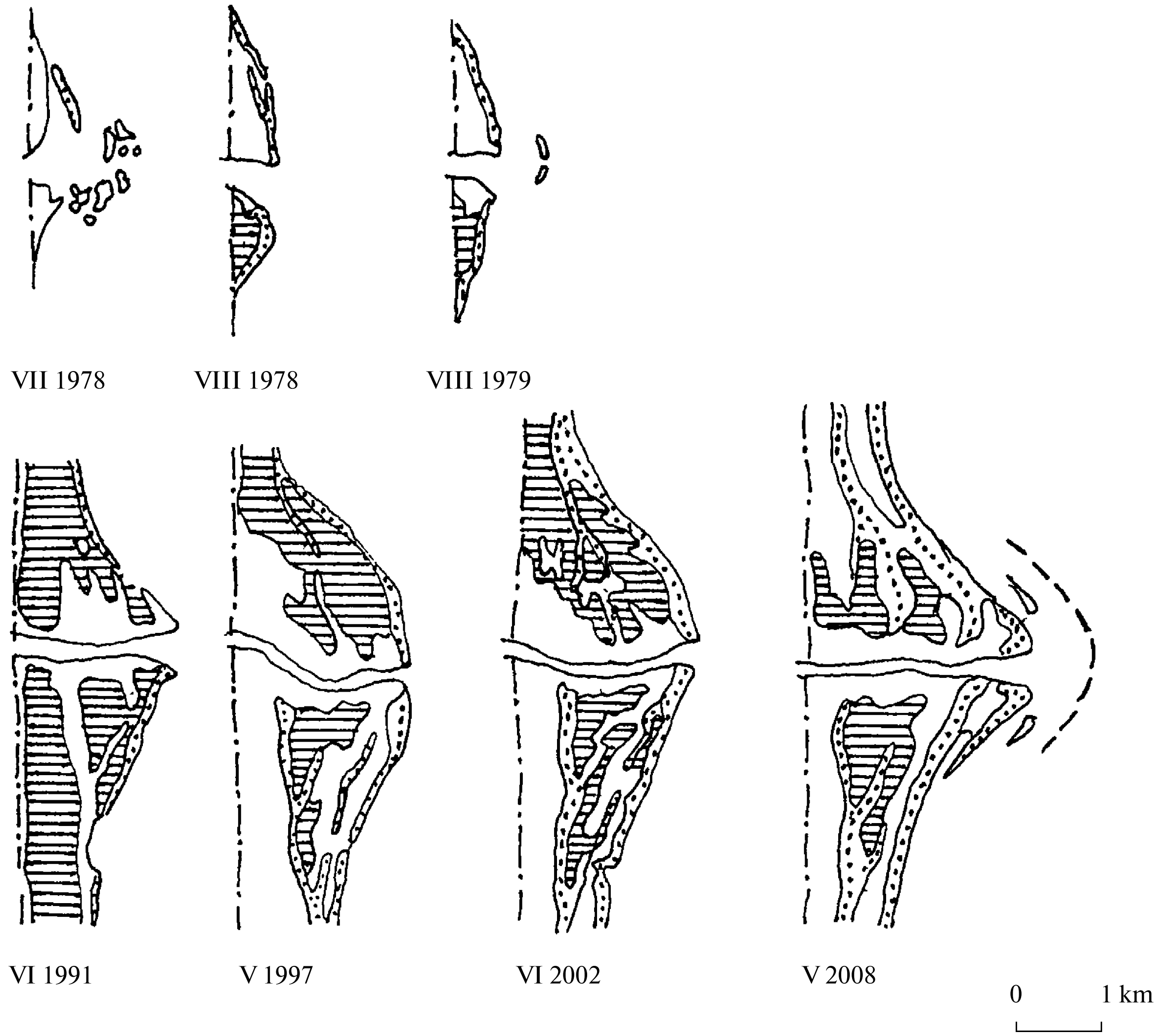


Fig. 9. Schemes of the evolution of the New Delta of the Terek in 1978–2008.

erated the protrusion of the New Delta into the sea. In the interval IVb, (1983–1995), in the period of abrupt sea level rise, the domain of rapid sediment accumulation and water level rise embraced almost the entire Kargalinskii Proryv Branch. Since the volume of backwater prism at the reserve canal mouth caused by sea level rise was far less than the volume of river sediments, the New Delta of the Terek continued protruding into the sea, notwithstanding the level rise. In the interval IVc (1995–present time), small change in bed elevations and water level, accompanying sea level variations, took place in the lower part of the Kargalinskii Proryv Branch. The processes in the intervals of the IV stages are shown in Figs. 7–9 and Tables 7 and 8.

The elevations of both bed and water level in the channel of the Kargalinskii Proryv Branch will apparently continue in the future. This process can be disturbed only by a considerable change in Caspian Sea level or a new large break of the channel.

CHANGES IN THE STRUCTURE AND REGIME OF THE SULAK MOUTH

The History of Evolution of the Sulak Mouth before the Formation of the Present-Day Delta

In the periods of Caspian Sea level standing low, the Sulak formed a common delta with the Terek. The DCL of this delta lied far to the east from the present-day shoreline. A higher sea level, the Sulak apparently emptied independently into the Caspian Sea south of its present-day mouth, as can be seen from the distinct marks of old delta branches in space photographs. In some periods, the Sulak emptied into a vast bay (the predecessor of the present-day Agrakhanskii Bay), whose eastern shore was blocked by a large barrier bar, that had formed because of wave destruction of Terek deposits and old protrusion deltas of the Sulak. Thus, Agrakhanskii Peninsula gradually formed, which was oriented northward—toward the predominant south-eastern waves and alongshore sediment flux [29].

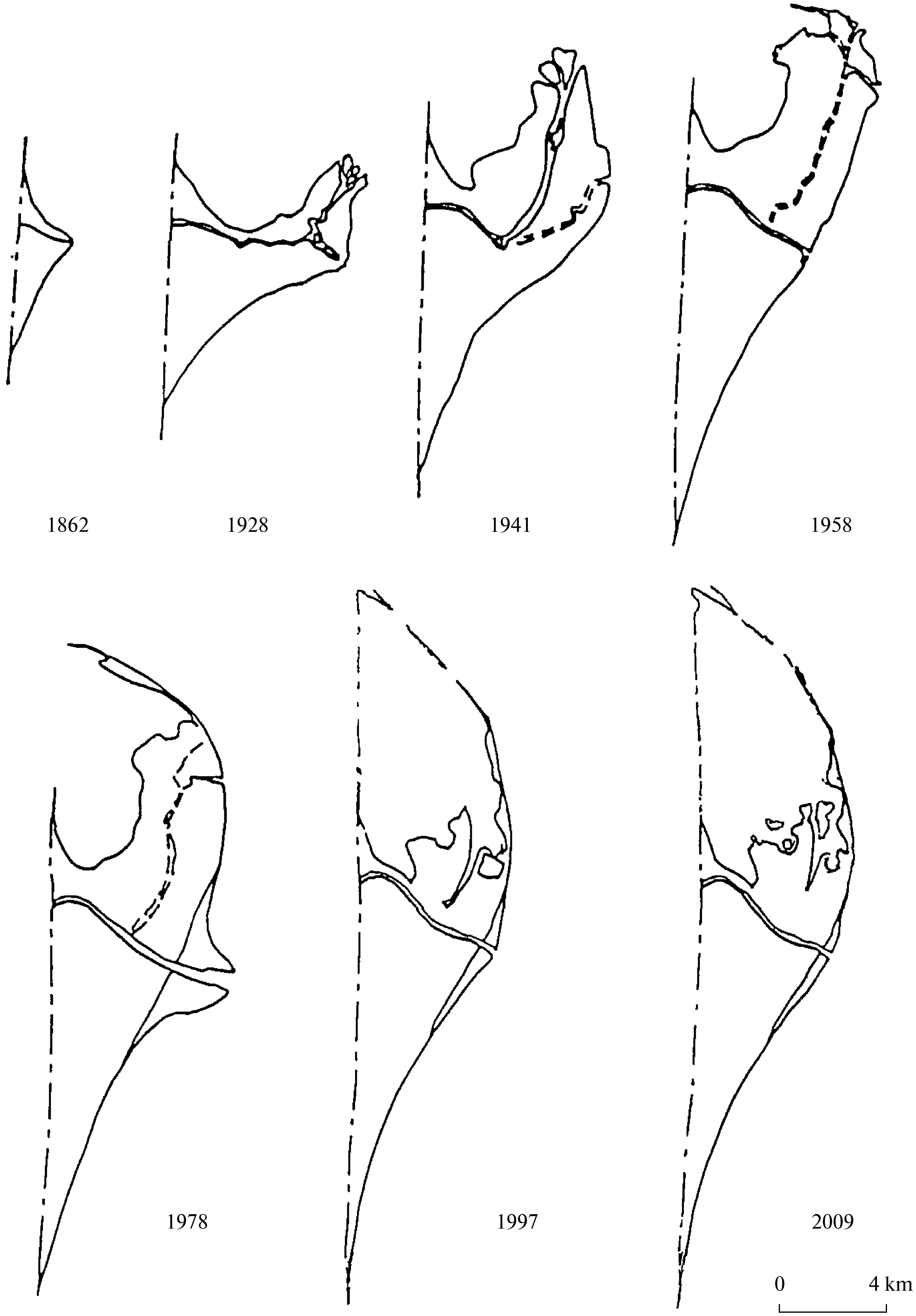


Fig. 10. Schemes of the changes in the Sulak delta from 1862 to 2008.

Table 9. Morphometric characteristics of the Sulak delta (its length along the main channel L, area F, area change ΔF, DCL width B_{DCL})

Year	H_s, m BS	L, km	F, km^2	B_{DCL}*, km	ΔF	
					km^2	km^2/year
1862	–25.92	2.22	6.20	9.0		
					8.1	0.2
1913	–26.21	3.29	14.3	12.0		
					16.2	1.1
1928	–26.07	9.10	30.5	22.5		
					4.9	4.9
1929	–25.88	5.75	35.4	22.5		
					13.4	1.5
1938	–27.25	10.24	48.8	27.0		
					2.2	0.7
1941	–27.84	11.30	51.0	29.0		
					6.7	1.1
1947	–27.75	10.93	57.7	30.0		
					1.4	0.7
1949	–27.81	11.60	59.1	33.0		
					3.3	1.6
1951	–28.13	12.44	62.4	33.5		
					–0.9	–0.3
1954	–28.26	12.86	61.5	33.5		
					0.6	0.2
1958	–28.21	5.57	62.1	32.5		
					2.6	0.6
1962	–28.53	6.58	64.7	32.5		
					5.9	0.4
1978	–28.95	7.90	70.6	33.5		
					–5.7	–1.4
1982	–28.23	7.38	64.9	33.5		
					–18.5	–2.1
1991	–27.26	6.38	46.4	27.5		
					–1.3	–0.2
1997	–26.95	6.32	45.1	27.0		
					–1.4	–0.5
2000	–27.10	6.30	43.7	27.0		
					0.5	0.1
2009	–27.21	6.00	44.2	27.0		

* Without Sulakskaya spit.

The most reliable data on Sulak mouth development are available from about the second half of the XVIII century. In this time, the Sulak emptied into the southern part of Agrakhanskii Bay and formed a bayhead delta there. Such delta can be clearly seen in the map compiled under the supervision of admiral S.I. Nagaev in 1793 and published in 1796 [35]. The later breaking of the river through the coastal barrier accumulative forms (barrier bars and wave-cut bars) into the open sea could be facilitated by water level rise in river delta, caused by the protrusion of Sulak channel into the shallow Agrakhanskii Bay, and the high sea

Table 10. Regression equations between sea level H_s, m BS, and the delta areas of the Sulak and Kura F, km^2, in different periods (r is correlation coefficient)

Delta of	Period	Regression equation	r
Sulak	1929–2009	$F = -12.872H_s - 299.36$	–0.9623
	1929–1978	$F = -11.945H_s - 264.32$	–0.9695
	1929–1954	$F = -11.261H_s - 256.66$	–0.9514
	1958–1978	$F = -11.617H_s - 266.01$	–0.9898
	1978–2009	$F = -14.710H_s - 353.58$	–0.9838
Kura	1929–2008	$F = -31.812H_s - 730.56$	–0.9806
	1929–1976	$F = -30.869H_s - 703.55$	–0.9984
	1929–1946	$F = -33.551H_s - 774.01$	–0.9999
	1962–1976	$F = -29.545H_s - 666.93$	–1.0000
	1976–2008	$F = -33.279H_s - 772.39$	–0.9625

level in the late XVII—early XIX (the highest in the historical time) [22, 54]. Agrakhanskii Peninsula can also be clearly seen in Nagaev's map. The map compiled by A.E. Kolodkin (1816) and the Caucasus Region Map (1847) show the Sulak flowing simultaneously into Agrakhanskii Bay and the open sea. Both directions of Sulak runoff persisted in the XIX century.

The Initial Stage of Formation of the Present-Day Sulak Delta

The primary delta of the Sulak was first shown as a small beak-like lobe in the map of N. Ivashintsev (1862) and next on the map of European Russia of 1913 (Fig. 10). According to data improved by the authors of this paper, the delta area in those years was 6.20 and 14.3 km^2, respectively (Table 9). Later, Sulak delta started rapidly protruding into the sea, which seems to be facilitated by the complete turn of the river toward the open sea. By 1920, the length and the area of the primary delta have reached ~7.5 km and 18 km^2, respectively [17, 35]. The reverse extrapolation of the plot of the Sulak delta area increase (Fig. 7) made it possible to approximately determine that the formation of the present-day delta of this river in the open coast of the Caspian Sea started about 1810.

Data in Figs. 7 and 10 and Table 9 show that the delta increase was first slow, but since the late XIX (after the Sulak branch flowing into Agrakhanskii Bay died), the growth rate of the delta increased considerably. Under the conditions of relatively stable sea level (from 1862 to 1928, it dropped by as little as 15 cm), the protrusion of Sulak delta into the sea was mostly active, i.e., determined by the deposition of river sediments in the coastal zone of the sea. In 1862–1928, the delta increased its length and area from 2.22 to 9.1 km (by 6.9 km within 66 years with the mean rate of 104 m/year) and from 6.2 to 30.5 km^2 (by 24.3 km^2, 0.37 km^2/year), respectively (Table 9).

From that time, the Sulak delta developed by successive channel breakings followed by the formation of particular subjoined deltas (delta lobes) (Fig. 9). Supposedly, in 1920, water broke through the left mouth spit, and the first particular subjoined delta of the Sulak, oriented toward northeast, started forming. By 1928, the length of the new channel has reached 9.1 km. The old delta lobe in the mouth part experienced wave erosion, and the length of the old channel decreased by about 0.5 km to become 7 km in 1928.

Changes in the Regime and Structure of the Sulak Delta in the Period of Considerable Drop in Sea Level (1929–1977)

In period 1929–1977, sea level dropped from –25.88 to –29.01 m BS, i.e., by 3.13 m (Table 2). This drop had an extremely strong effect on the development of Sulak delta. Its passive protrusion into the sea started playing a considerable role in its increase. The actual increase in delta area in 1929–1978 was 70.6 – 30.4 = 40.2 km^2 (Table 9), while its mean rate over 49 years was 0.82 km^2/year. As shown above, the active protrusion of the Sulak delta in the initial period of its development was ~0.37 km/year. Later, as the delta reached greater sea depths, this value dropped to 0.25 km^2/year and in 1929–1977, it averaged ~0.3 km^2/year. Thus, in 1929–1977 the contribution of delta passive protrusion was 0.82 – 0.3 = 0.52 km^2, or ~63% of the total delta protrusion into the sea.

The large contribution of the passive protrusion to the Sulak delta development in 1929–1977 is also confirmed by the regression equation for the dependence of delta area on sea level in different periods (Table 10). A 1-m drop of sea level caused an increase in delta area by 11–12 km^2.

This stage of the development of the present-day Sulak delta can be divided into two intervals: 1929–August 1957 (the development of the second subjoined delta) and August 1957–1977 (the development of the third subjoined delta).

1929–August 1957. In 1929, water broke through the very narrow (300–350 m in width) left mouth spit (Fig. 10). Old-timers say this breaking was provoked by fishermen digging a small ditch through the mouth spit. The new delta lobe started rapidly protruding north-northeastward. The rate of increase in delta area in that period was the largest all over the history of the present-day Sulak delta (Table 9, Figs.7 and 10). The rapid protrusion of the delta was facilitated by the shallowness of this part of the nearshore area, the relative protection of the new lobe by the body of the old delta against the impact of southeastern sea waves, the large sediment yield or the river in that time, and a drop in sea level. During 1929–1957, the second subjoined particular delta of the Sulak protruded 7.2 km northward, and the area of the entire delta increased almost twofold (Table 9, Fig. 7). In that period, the sea level dropped by 2.46 m; with the bed slope in the delta for-

Table 11. Water surface slopes in the reach of Sulak gauge—the sea in different years at water discharge of 200 m^3/s

Year	Level elevations, m BS		Level difference, m	Length of the reach, km	Slope, 10^{-5}
	Sulak gauge	Makhachkala gauge			
1934	–25.55	–26.27	0.72	6.6	10.9
1937	–25.78	–26.92	1.14	8.6	13.2
1940	–26.40	–27.76	1.36	9.7	14.0
1954	–26.90	–28.26	1.36	11.4	11.9
1957*	(–26.9)	–28.34	1.4	11.5	12.2
1957**	(–26.9)	–28.34	1.4	4.0	35.0
1958	(–27.4)	–28.21	0.80	4.1	19.5
1967	–28.00	–28.37	0.37	5.7	6.4
1978	(–28.1)	–28.95	0.80	6.4	12.5
1980	–27.75	–28.57	0.82	6.1	13.4
1990	–27.25	–27.59	0.34	4.8	7.1
1992	–26.75	–27.09	0.34	4.8	7.1
1997	(–26.5)	–26.95	0.40	4.8	8.3
2000	(–26.9)	–27.10	0.20	4.8	4.2
2009	(–26.9)	–27.21	0.30	4.5	6.7

Notes: * before the shortening of channel length;
** just after it.

mation zone of ~0.5‰, the passive protrusion of the delta would be 4.9 km. i.e., 68% of the actual value.

In 1934–1957, water level at Sulak gauge showed a peculiar behavior. Nowadays, this gauge is situated 5 km from the sea, but in the past, this distance varied depending on whether the river channel length was decreasing or increasing (after breakings) (Table 11). Figure 8 clearly shows that up to 1957, water level at Sulak gauge declined simultaneously with sea level drop. In 1934–1957, the levels dropped by 1.4 m at Sulak gauge and by 2.1 m in the sea. The result was that the level differential in the reach from Sulak gauge to the sea increased from 0.7 to 1.4 m (Table 11). The difference between level changes in the sea and at Sulak gauge is due, first, to the time lag in the erosion process that accompanies sea level drop and, second, to certain compensating effect of the mouth elongation of Sulak channel, which in that period was ~4.9 km (Tables 9, 11). An indication to the erosion in Sulak mouth area in this period is the increase in water surface slopes (Table 11).

August 1957–1977. The specific features of Sulak delta development in this period were determined, first, by the artificial transfer of Sulak channel into the sea via a new, shorter route (Fig. 10) and, second, a farther drop of sea level. In August 1957, Sulak runoff was directed into the sea through an artificial canal ~2 km in length with southeastern direction. When the canal was opened, the old channel was blocked by a rock-fill dam. These hydroengineering measures were aimed to prevent the input of river sediments into Sulak Bay, which formed in the previous decades between the delta lobe that had protruded northward and the main shore. A berth and a fishermen office, established in this bay, now were situated in a silting zone.

Since August 1957, the third subjoined delta started forming at the canal mouth. This was called the New Delta of the Sulak as opposed to the entire Sulak delta, which had formed before August 1957 and was called the Old Delta of the Sulak [9, 17]. Until 1978, the development of the New Delta was taking place against the background of sea level drop (by about 0.7 m) and a relatively high sediment yield in the river (this runoff significantly dropped only after 1974 (Table 1)). The total area of the Sulak delta increased from 62.1 to 70.6 km^2 during 1957–1978, and the increase in the entire delta was somewhat greater than that of the New Delta, thus suggesting a passive increase in the land area in the northern part of the Old Delta because of sea level drop. The area of the New Delta has reached ~1.8 km^2 by 1962 and ~5.0 km^2 by 1978 [17]. In period 1957–1977, sea level dropped by 0.67 m. This should have caused a small passive protrusion of the Old Delta (at the nearshore bed slope i_{nsh} = 1.7‰ [35]) and by 394 m in the zone of the New Delta 1.5‰ by 447 m and a protrusion by 394 m near the New Delta (at i_{nsh} = 1.7‰ [35]). The New Delta of the Sulak protruded by 1.7 km in this period, the fact that demonstrates the predominance of active protrusion of the New Delta of the Sulak into the sea in that time (the active protrusion accounted for ~77%

of the total). Parallel with the protrusion of the New Delta into the sea, wave erosion of the eastern part of the Old Delta was taking place. By 1962, the products of this erosion formed a new, northwestward-oriented sand spit on the northern extremity of the old delta lobe (Fig. 10). Later the length of this spit, named Sulakskaya Spit, rapidly increased, reaching ~7 km by 1978 and practically blocking the entrance into Sulak Bay.

Because of a decrease in channel width by 7.5 km (Tables 9, 10), the slopes of water surface in Sulak mouth reach abruptly increased (from $\sim 12 \times 10^{-5}$ to 35×10^{-5}) (Table 11) as well as the flow velocity. This (along with sea level drop) facilitated very heavy erosion of the channel in its mouth reach with the effect propagating several tens of kilometers upstream the river. This process, gradually decaying, continued for 20 years [9, 17, 38]. In 1957, because of erosion, bed elevation at Sulak gauge dropped by 0.9 m and water level, by 0.8 m [9]. In the process of incision, the channel was shifting nearly parallel to itself [38].

Changes in the Structure and Regime of the Sulak Delta in the Period of Considerable Sea Level Rise (1978–1995) and in the Following Years

In 1978–1995, sea level rose by 2.35 m (Table 2). This had a significant effect on the structure and hydrological regime of the Sulak delta. An accompanying factor was the abrupt anthropogenic decline in Sulak sediment yield since 1975 (Table 1). The main consequences of the impact on the Sulak delta of the factors mentioned above were the upstream propagation of the backwater effect from the rising sea level; the inundation of lowland delta areas, especially, in its northern part, on the shore of Sulak Bay, and in the New Delta, a considerable decrease in delta area; stronger wave erosion of the eastern shore of the delta, the narrowing and separation of Sulakskaya Spit into several fragments, the formation of a bar–lagoon complex along DCL.

The backwater effect of the sea caused water level rise at Sulak gauge (Fig. 8), which has reached ~1.9 m by 1995, i.e., it was slightly less than the sea level rise. In the zone of backwater propagation, the slope of water surface appreciably decreased (Table 11). The deficiency of river sediments after 1974 (when the Chirkey Reservoir was constructed) prevented the rapid deposition of sediments and channel bed rise (as was the case in the Terek delta). Therefore, the rise of water level at Sulak gauge was accompanied by a slower rise of the bed, resulting in an appreciable increase in the mean depth (approximately, from 1.8 to 2.5 m).

Changes in the Sulak delta as a whole were more significant. The delta experienced high inundation (Fig. 10). From 1978 to 1997, its area decreased from 70.6 to 45.1 km^2, i.e., by 25.5 km^2 or 36%. The high inundation of the Sulak delta is radically different from the delta at the mouth of the Kargalinskii Proryv Branch at the Terek mouth. This is because the considerably decreased sediment yield in the Sulak was not able to fill the backwater prism that had formed because of sea level rise [40, 46].

An important conclusion was derived from the correlation of the Sulak delta area F and sea level H_s in the period of its rise (Table 10). The correlation between F and H_s showed the same closeness as those for the period of sea level drop. Moreover, the character of correlation between F and H_s in the period of sea level rise was similar to that for the period of sea level drop, but reverse. At the same time, the relationship between F and H_m over the entire period from 1929 to 2009 was found to be universal, so that it can be used to calculate F from H_s during either level rise or drop. This suggests the strong dependence of the size of the present-day Sulak delta on sea level elevation.

Despite a drop of sea level since 1995 (by about 0.4 m), a tendency toward a decrease in the area of the entire (including the New Delta) Sulak delta persisted to year 2000 (Table 9). Clearly, this cannot be attributed to land inundation because of sea level rise. Apparently, the recession of the shore in this case is due to its wave erosion in combination with very low river sediment yield. Space photographs made in 2008 and 2009 show that the intense inundation of Sulak delta has practically stopped. Sulakskaya Spit, which has reappeared by 1997, still shows a slow increase in the northern direction.

In the future (under the conditions of small river sediment yield), changes in the Sulak delta will be mostly dependent on variations in the mean sea level. In this case, variations in delta area in the case of both rise and drop of sea level can be approximately evaluated by the universal equation for period 1929–2009 (Table 10).

VARIATIONS IN THE STRUCTURE AND REGIME OF THE KURA MOUTH

The History of Kura Mouth Evolution before the Formation of the Present-Day Delta

During the transgression of the Caspian Sea, Kura–Araksinskaya Lowland transformed into a shallow bay cutting inland with separate ancient deltas of the Kura and Araks forming within it. In periods of deep regressions, the common delta of the Kura and Araks protruded into the sea far eastward from its present-day position. During the latest, Novokaspian transgression, a series of deltas formed, first separately at the mouths of the rivers of Kura and Araks and next, when the Araks became Kura's tributary, at the mouth of the latter river. According to Herodotus, Ptolemy, and Strabo, 2000–2500 years ago, the rivers of Araks and Kura had separate deltas. In that period, the Kura has formed the so-called Mil'sko–Karabakhskaya delta [63]. The subsequent deltas—in the center of

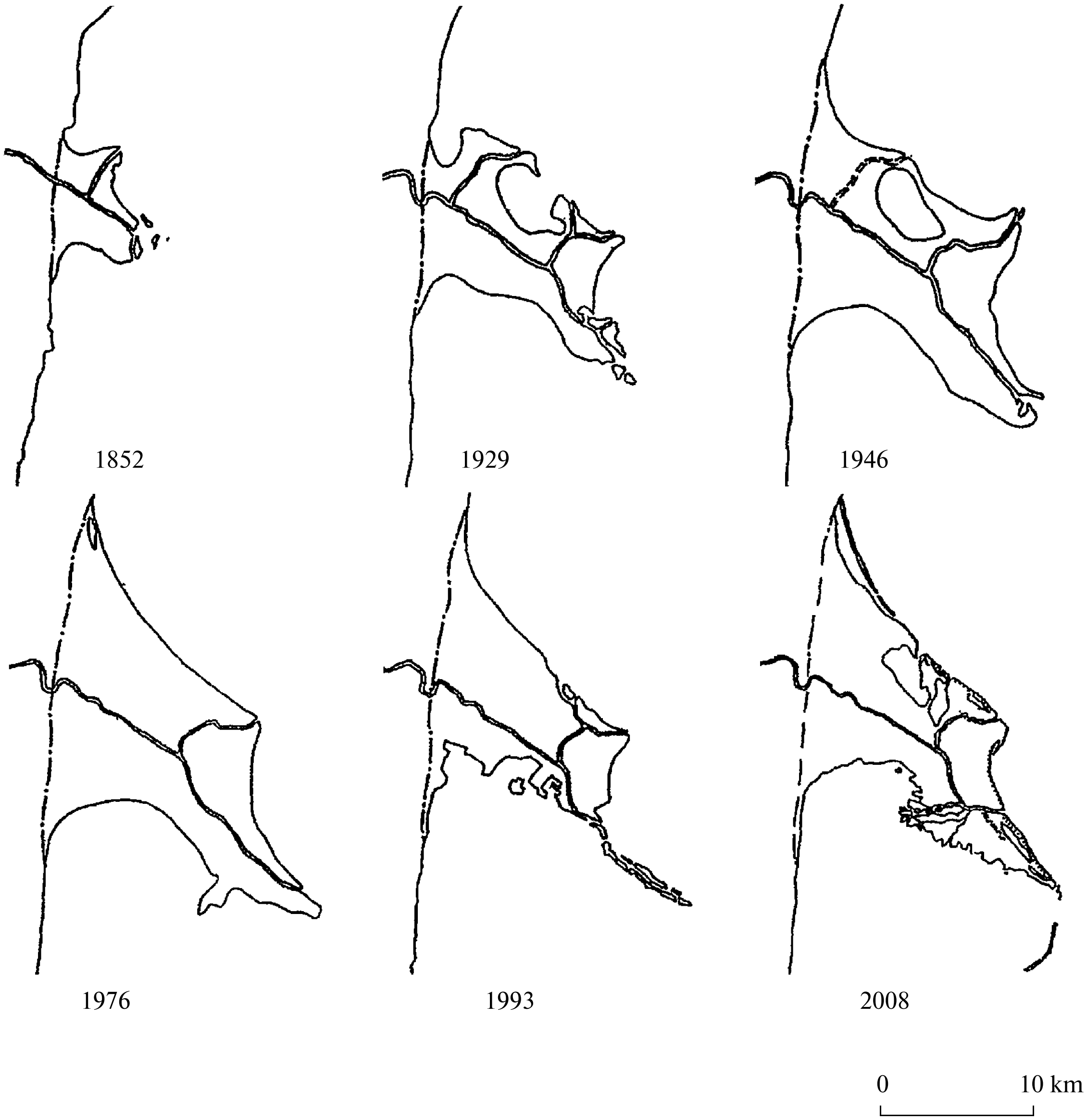


Fig. 11. Schemes of the changes in the Kura delta from 1852 to 2008.

Shirvanskaya Steppe (the second), Muganskaya delta (the third), in the southeastern Shirvan (the fourth), Khillinskaya delta (the fifth), and the three successive Sal'yanskie deltas in Kyzylagachskii Bay—formed only at the Kura mouth chequer-wise with respect to river channel [19]. In the late XVIII century, the latest of the Sal'yanskie deltas existed on the sea coast [19, 63].

Similarity and Difference in the Development of the Modern Kura and Sulak Deltas

After the breaking of river water along the new route toward the sea in the late XIX–early XX century, the present-day Kura delta started forming (Fig. 11). The reverse extrapolation of the plot of Kura delta area variation (Fig. 7) yielded the approximate date when this delta started forming—1810. As shown above, it was the time when the present-day Sulak delta started forming. This is not a coincidence: apparently, sea level at that time was at its highest elevation in the past millennium [22, 54]. The similarity in the development of the modern deltas of the Kura and Sulak even wider. Those deltas formed at a steep nearshore area under sea level variations with same directions and magnitudes, and, until the mid-XX century, at large river sediment yield. In Kura delta, as well as in Sulak delta, both natural channel breakings, as is typical of deltas of rivers with large sediment yield [31], and artificial changes of channel network structure took place.

Table 12. Morphometric characteristics of the Kura delta (length along the main branch L, area F, delta coastline width B_{DCL}

Year	H_s, m BS	L, km	F, km^2	B_{DCL}, km	Changes			
					ΔH_s		ΔF	
					m	cm/year	km^2	km^2/year
1852	–25.92	7.7	29	18.8				
					–0.07	–0.8	10	1.2
1860	–25.99	9.4	39	22.5				
					0.29	0.6	45	1.0
1907	–25.70	14.7	84	51.5				
					–0.18	–0.8	10	0.4
1929	–25.88	17.5	94	54.0				
					–0.28	–14.0	10	5.0
1931	–26.16	20.0	104	71.0				
					–1.71	–11.4	57	3.8
1946	–27.87	21.7	161	56.0				
					–0.66	–4.1	15	0.9
1962	–28.53	22.5	176	56.0				
					–0.44	–3.1	13	0.9
1976	–28.97	22.7	189	60.0				
					0.40	10.0	–9	–2.2
1980	–28.57	24.0	180	62.0				
					1.61	12.4	–66/–69*	–51/–5.3*
1993	–26.96	23.7/14.0*	114/111*	67.0/50.8*				
					–0.14	–2.0	16/19*	2.3/2.7*
2000	–27.10	18.0**	130***	63.5				
					–0.11	–11.0	6.0	6.0
2001	–27.21	18.0**	136***	62.0				
					0.07	1.0	6.0	0.8
2008	–27.14	17.5	142	64.0				

Notes: * less the islands as former natural levees in the inundated part of the Southeastern Branch;
** assuming the largest bypass in the breach;
*** less the area of coastline bars.

However, the development conditions of the Kura and Sulak deltas showed some important differences. First, the values of water runoff and sediment yield for those rivers significantly differed (Table 1). Kura water runoff was greater than that of the Sulak by a factor of 3.7 before river runoff regulation began and 3.1 under river runoff regulation; suspended sediment yield of the Kura before the regulation of both rivers was 2.4 times greater than that of the Sulak, while after the establishment of regulation, it was 6.7 times greater. Because of significant differences between sediment yield in the rivers, Kura delta has reached the area of ~190 km^2, while Sulak delta, only ~51 km^2 (Tables 9, 11). The rate of growth of Kura delta was ~3.7 times greater than that of Sulak, and the contribution of active protrusion in the increase of this delta was appreciably greater than that of Sulak delta. Second, the directions of predominant waves in the formation areas of the deltas were radically different (from the northeast at Kura DCL, and from southeast at Sulak DCL) and, accordingly, the directions of alongshore sediment flux and the extension of the large marine accumulation spits formed by them.

The Initial Stage of Kura Delta Formation

After the breaking of river water into the sea in the eastward direction and the gradual concentration of Kura runoff in a single channel, the delta started rapidly growing (Figs. 7, 11, Table 12). In A.E. Kolodkin's map (1816), the Kura is shown to have only one branch discharging into the sea and still forming no delta lobe [34]. Sal'yanskaya delta, situated south of the new one, has experienced a destructive impact of sea waves. The products of its erosion gradually formed the vast Kurinskaya Spit, oriented southward and separating Kyzylagashskii Bay from the sea.

In 1852, Kura delta (sea level lied at –25.92 m BS) had already two branches—the Norheastern Branch and the main Southeastern Branch (Fig. 11). The southeastern direction in the runoff in Kura delta persisted over a long time. Against the background of a relatively stable or weakly decreasing sea level, the protrusion of Kura delta into the sea in the late XIX–early XX centuries was first slow, notwithstanding the considerable sediment yield (Fig. 7). At the same time, delta protrusion into the sea was mostly active and rather rapid—from 0.4 to 1.2 km^2/year (Table 12).

Changes in the Structure and Regime of the Kura Mouth in the Period of Considerable Sea Level Drop (1929–1977)

The results of surveys in Kura delta in 1931, 1946, 1962, and 1976 demonstrate considerable changes in its morphological and morphometric characteristics (Fig. 11, Table 12) under the combined effect of drop in Caspian Sea level and a decrease in river sediment yield after the construction of the Mingechaur Reservoir in 1952.

During 1929–1946, the projection at the mouth of the Southeastern Branch or Navigable Kura (this is how the former Southeastern Branch was called) protruded by 4.2 km, and the delta area increased from 94 to 161 km^2 or by 71% [34]. The rate of increase of the delta area in this period (5 km^2/year in 1929–1931 and 3.80 km^2/year in 1931–1946) were the largest throughout the development history of present-day Kura delta (Table 11), which is certainly due primarily to the abrupt drop of sea level at considerable river sediment yield. By 1962, the Northeastern Branch (then called the Old Kura) continued dying and Lake Yakopinskoe has dried out. In 1976, at the end of the period of the latest regression of the Caspian Sea, the delta was still protruding southeastward. By 1976, delta area has increased to 189 km^2 (the maximal value of the area of present-day Kura delta). In 1929–1976, the active protrusion of the delta into the sea coincided with the passive protrusion caused by sea level drop. This is well illustrated by the equations of the form $F = f(H_s)$ (Table 10).

As can be seen from Fig.12, until the early 1930s, the level at Ust'e gauge near Kura DCL varied in the same manner as the sea level. However, starting from the 1940s, its drop at this gauge showed a lag relative the sea level drop, because of the mouth elongation of the Southeastern Branch (the Navigable Kura), which in 1929–1976 amounted 5.2 km (Table 12). The difference between the mean annual water levels at Ust'e gauge and in the sea gradually increased, reaching 0.4 m in 1950, 0.6 m in 1960, 0.7 m in 1970, and 0.8 m in the year of minimal sea level (1977) (Fig. 12). This figure shows also that the decrease in the level extended along Kura mouth area upstream of Sal'yany gauge (85 km from the sea in the early 1970s).

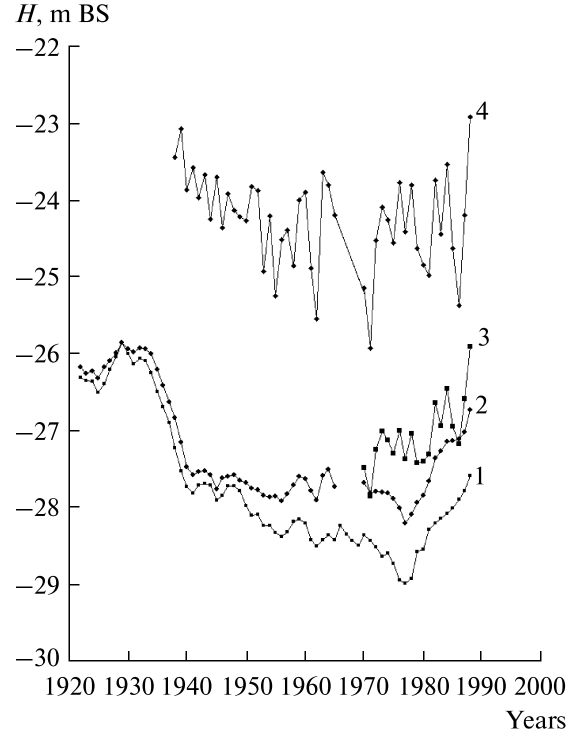


Fig. 12. Changes in annual water levels at (1) Makhachkala marine gauge and at (2) the Ust'e, (3) Karavelli, and (4) Sal'yany gauges at the Kura mouth.

Changes in the Structure and Regime of the Kura Mouth in the Period of Considerable Rise of Sea Level (1978–1995) and in the Subsequent Years

In 1978–1995, Kura delta was developing at river sediment yield lower than that before 1953 and, which is most important, against a considerable rise of Caspian Sea level. In 1980, accumulative processes still dominate in the delta, and the protrusion of the Southeastern Branch into the sea continued (Fig. 11).

Very significant changes in the delta have taken place by 1993, when sea level reached the elevation of –29.96, exceeding its level in 1980 by ~1.6 m. The major portion of the delta projection was inundated. Delta area has decreased considerably since 1980 (by 66 km^2 or by 37%) and amounted to 111 km^2

(Table 12). The dependence of delta area on sea level in the period of its rise is described by formulas in Table 10. In the inundated part of the delta projection along the main delta branch, narrow land strips persisted—former channel banks, overgrown by reed, and, partially, soil dumps after dredging operation carried out in the branch in previous years.

The rise of sea level propagated upstream the Kura delta and mouth area over large distances (Fig. 12). Water level at Ust'e gauge (2.2 km from the sea in the 1970s) was rising almost synchronously with the sea level. At Karavelli gauge (27 km from the sea), water level has rose by ~1.2 m by the early 1990s. The backwater effect, propagated to Sal'yany gauge (85 km from the sea), caused a level rise here on the average by 0.6 m in the same period. This shows that the overall propagation distance of backwater effect into the river by 1995 was not less than 120 km.

Peculiar changes took place in the hydrographic network of the delta. In the period of high sea level, Kura water more actively flowed through gaps between islands in their chain along the right-hand bank of the Southeastern Branch. The result was the formation, seemingly, in 1993, of an erosion breaking at the right bank of the branch at its bend 8 km from its mouth and 4 km downstream of the source of the Northeastern Branch. The development of the breaking was facilitated by sea level rise and the very large water discharge during the flood in 1993. During sea level drop after 1995, which intensified the erosion in the breaking bypasses, the breaking completely intercepted the entire runoff of the Southeastern Branch. The major portion of the Southeastern Branch downstream of the breaking of 1995 was silted and overgrown by reed.

In 2005, a straight canal was dug in the eastward direction from the channel bend slightly upstream of the sources of breaking bypasses for the discharge of Kura water directly into the sea via a short distance with a twofold purpose: to prevent the further development of the breaking and to ensure the navigation through Kura delta. The division of the Kura into the new eastern channel; the Northeastern Branch, which became somewhat more active; and the Southwestern Breaking (Branch) still persisted by 2008. The old projection at the mouth of the former Southeastern Branch became 1 km shorter from 2001 to 2008. The products of its erosion are still forming the accumulative spit in southwestern direction. The length of New Kurinskaya Spit in 2001 was ~3 km; while in 2008, it has reached 5 km and turned (the northern end to the west, and the southern end to the south).

The further fate of Kura delta will depend on the direction and the magnitude of sea level changes. In case of both its drop and rise, the size of Kura delta can be approximately evaluated by using the universal for 1929–2008 regression equation (Table 10). However, it is clear that anyway, the new canal (its mouth can become the main place of new active delta formation process), the revived Northeastern Branch, and the southwestward breaking (if not blocked) will all continue functioning. The erosion of the old projection of the Southeastern Branch and the elongation of the New Kurinskaya Spit will also continue.

CONCLUSIONS

The mouths of largest rivers flowing into the Caspian Sea (Volga, Ural, Terek, Sulak, and Kura) differ in their geological history, structure, specific features of the evolution and landscape of their deltas, the degree of flatness or steepness of nearshore areas, the character of economic development of natural resources and local hydroengineering and water management activities. The water runoff and sediment yield and their natural and anthropogenic variations are also different.

Studies of the mouths of rivers flowing into the Caspian Sea, considering the differences mentioned above and the effect of large-scale sea level variations in the XX century, which are common for all rivers (a drop by 3.13 m in 1929–1977 and a rise by 2.35 m in 1978–1995), make it possible to establish universal regularities in the response of the structure and regime of any river mouths to changes in the external environmental factors.

The authors established that such response depends, primarily, on whether the variations in water levels in the sea and at delta coastlines coincide. At river mouths with steep (Terek, Sulak, Kura) or nearly flat nearshore areas (Ural), the levels in the sea and at DCL practically coincide and vary (either rise or drop) synchronously. At such mouths, sea level variations rapidly penetrate into the deltas. At the Volga mouth, with its exceptionally flat and wide nearshore area, the sea level drop in the 1940s–1950s broke down the hydraulic interaction between delta streams and the sea, the nearshore area turned into a huge inundated weir with a wide crest, and the level drop in the delta ceased, notwithstanding the continuing drop in sea level. The level drop between Volga DCL and the sea reached ~2 m. The reverse process began during the level rise in the 1980s–1990s—the gradual inundation of the nearshore area—and water level at Volga DCL started increasing only in the mid-1990s and rose by as little as 0.5 m.

The level drop in 1929–1977 accelerated the protrusion into the sea of the deltas of all rivers considered here, except for the Volga, where delta increase practically ceased in the 1950s for the reasons mentioned above. In the process of delta growth in the rivers of Ural, Sulak, and Kura, the passive protrusion, caused by sea level drop, predominated over the active one, caused by river sediment deposition. Sea level drop led to the formation in the deltas of a curve of hydraulic decline and caused intense bed erosion, which gradually propagated upstream. At the mouth of the Terek, which then emptied into the shallow Agrakhanskii Bay, the expected drop in water level and channel incision were not observed; instead, water surface slopes increased, and the elevations of water and bed levels rose. The process of sediment accumulation and bed rise was aggravated by the rapid protrusion of a particular delta of the Terek into Agrakhanskii Bay. The reverse erosion in Terek and Sulak deltas increased because of an abrupt decrease in Terek channel length resulting from the breaking of the dam at the reserve canal in 1973 and its reopening in 1977; similar effect in the Sulak was observed after the river was artificially connected with the sea via a new canal in 1957.

Sea level rise in the mouths of all rivers except for the Volga caused the formation of backwater zones, extending over vast distances from the sea. The propagation distance (the sea level rise being the same) was the greater, the less was the slope of water surface in the channel. Sea level rise caused also the formation of the so-called backwater prism. In the cases where the runoff of delta-forming river sediments over the period of sea level rise exceeded the volume of the backwater prism, as was the case, for example, at the mouth of the main channel in the Terek delta (Kargalinskii Proryv Branch), the delta continued, though slowly, protruding into the sea and increasing its height, notwithstanding the rise in sea level. In the cases where river sediments were not enough to fill the backwater prism, as, for example, at the mouths of the Ural, Sulak, and Kura, the deltas were subject to high inundation. An important role in the inundation of Sulak and Kura deltas belonged to the decrease in sediment yield after the construction of the Chirkey (1974) and Mingechaur (1952) reservoirs.

Water level rise on Volga DCL was much less than the rise of sea level; therefore, the distance of backwater effect propagation into its delta branch was relatively short and the coastal part of the delta has practically avoided inundation.

Sea level drop, artificial deepening of the channel or a reduction of its length, and natural breakings lead to the redistribution of water runoff in favor of the new, shorter or deeper delta branch; at the same time, lateral or old branches may lose of their runoff or die. Conversely, sea level rise often leads to the revival of lateral, even dead delta watercourses.

Sea level variations also cause considerable changes in the natural conditions at river mouths in general. Thus, the recent rise in Caspian Sea level caused not only inundation of the coastal parts of some deltas, but also to the intensification of their wave erosion and the formation of bar–lagoon complexes along delta shores, the extension of reeds in shallow nearshore areas, rise of groundwater level, and the hydromorphization of vegetation in the coastal parts of deltas.

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