Water Resources, Vol. 30, No. 5, 2003, pp. 495–508. Translated from Vodnye Resursy, Vol. 30, No. 5, 2003, pp. 541–554.

HYDROPHYSICAL PROCESSES

Hydrological and Morphological Processes in the Kura River Delta

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Received April 1, 2002

Abstract—Peculiarities of the development of the Kura Delta over the last 200 years are discussed. As shown, changes in the delta were greatly affected by the Caspian Sea level drop during 1929–1977 and its rise during 1978–1995 as well as by natural and human-induced variations in the water and sediment runoff of the river. It was noted that the delta area decreased by nearly 40% as a result of the sea level rise. The following significant changes in the Kura Delta were revealed in recent years using space images: river water rushed through the right mouth spit and, hence, the main Southeastern Branch was devoid of its flow and a new sea spit began its formation in the branch mouth using wave-cut products.

INTRODUCTION

By hydrological and morphological processes in river deltas are meant the interrelated dynamics of water and sediments (including their distribution by branches) and the dynamics of bottom and bank configurations (including changes in the channel network and delta coastline) [10]. Such processes in the Kura Delta are of particular interest, because the delta has undergone serious changes in spite of its juvenile age (the modern delta started its formation early in the XIX century). However, the delta development processes have been insufficiently studied. The only large monograph concerning the study of the Kura River mouth was published in 1971 [4]. It is now out of date. Hydrological and morphological processes in the Kura Delta were considered as of the early 1960s. Therefore, the impact on the delta of the Caspian Sea level drop in the 1970s and the sea level rise during 1978–1995 could not be taken into account in [4].

The Kura Delta ranks fourth in area (after the deltas of the Volga, Terek, and Ural rivers) on the Caspian Sea coast. Similar to the Sulak Delta, the modern Kura Delta was formed in the open deep offshore zone under the condition of considerable river sediment runoff; it looks like a typical lobe protruded far into the sea. In the 1960s–1970s, (before the recent considerable rise of the Caspian Sea level) the Kura Delta area F was about 180 km^2, the length L along the main channel was 23 km, the river fan volume approximated 3.5 km^3.

The modern Kura Delta represents a portion of the Kura–Araks Lowland with steppe and semisteppe landscapes and saline soils. In the last 50 years, the delta drainage system has two branches, i.e., the Southeastern Branch (the Navigable Kura) and the disappearing Northeastern (the Old Kura) Branch. The modern delta has some dry depressions, which represent channels of disappeared branches and desiccated lagoons and lakes. The delta is used for farming and fishery and also for navigation.

The Kura Delta is of particular interest for researchers primarily due to the fact that it serves as an example of an active delta in the open nontidal near-shore zone with moderate wave activity and considerable level variations over the period of many years. Up to the late 1980s, the delta was studied by Azerbaijan and Russian scientists [1–4, 6, 10]. Since the end of the 1980s, the studies of the Kura Delta were drastically reduced and the last map of the Kura Delta was prepared using the land-based data and aerophotographs made in 1962. Meanwhile, noticeable changes related to the Caspian Sea level drop and then rise have occurred over the last 20–30 years. At present, the only available monitoring method of the Kura Delta variations is the use of space images. This article is aimed at analyzing the present hydrological and morphological processes occurring in the Kura Delta through correlation of results of interrupted hydrometric observations and data on topographic surveys and space images. The analysis was made on the basis of methods of river delta studies worked out recently in Russia [9–11]. Close attention was paid to the impact of considerable sea level variations and human-induced reduction of the river sediment runoff on the processes occurring in the Kura Delta.

FACTORS OF THE KURA RIVER DELTAFICATION

The main factors responsible for the character of present hydrological and morphological processes in the mouth area of the Kura River are water runoff and sediment runoff in the river, sea waves and fluctuations of the Caspian Sea level. The sediment runoff of the Kura River with its natural and human-induced variations is the main factor influencing the intensity of the

Table 1. Main characteristics of water and sediment runoff of the Kura River

Time period	Q_0, m^3/s	W_0, km^3/year	Q_{max}, m^3/s	Q_{min}, m^3/s	R_0, kg/s	W_R, million t/year	s_0, kg/m^3	R_{max}, kg/s
1930–1952	570	18.0	1680	148	1260*	39.7*	2.18*	9500**
1953–1993	472	14.9	1165***	166***	500	15.8	1.06	5680***

* Over the period of 1934–1952 [3].
** Over the period of 1948, 1950–1952.
*** Over the period of 1953–1988.

Table 2. Some statistical characteristics of water and suspended sediment discharges of the Kura River

Time period	Water runoff			Time period	Water runoff		
	Q_0, m^3/s	ΔQ, % *	C_v		R_0, kg/s	ΔR, % *	C_v
1930–1952	570	3.5	0.17	1948–1952	1100	10.7	0.24
1953–1993	472	4.7	0.30	1953–1993	500	11.3	0.72
1930–1993	507	3.3	0.27	1948–1993	565	10.4	0.70

* Mean square deviation.

river mouth fan and delta increase. Sea waves cause degradation of deltaic deposits and changes in the configuration of the delta coastline. Water level fluctuations over the period of many years either contribute to delta protrusion into the sea (in case of the sea level drop) or slow down this protrusion or even result in submergence of some delta areas (in case of the sea level rise).

Water and Sediment Runoff of the Kura River

The data of the hydrological station of Sal'yany located 85 km from the sea are usually used to characterize the runoff variability in the Kura River mouth. The first attempt to assess water runoff at this point dates back to 1862 [4]. Since 1937, water discharges were regularly measured at this station with a break during the years of war (1941–1945). The runoff at the hydrological station of Sal'yany was not determined in 1937 and 1946 because of the discontinuities in measurements. The missing data were restored by the authors of this article using the relations between mean annual water discharges at the hydrological stations of Sal'yany and Sabirabad (or Surra), where observations over the water runoff were carried out since 1929.

Suspended sediment discharges R are being recorded at the Sal'yany station since 1948. It is impossible to determine the missing data (due to discontinuities in observations) over the previous period, because there is no close relation between Q and R. This results from the high (in comparison with Q) variability, errors in R measurements (caused by insufficiently developed methodology in those years) [3], and a short observation period prior to the commissioning of the Mingechaurskoe Reservoir. At the same time, by comparing the mean annual values of R for the Sabirabad and Sal'yany hydrological stations over the period of 1949–1952, it is possible to assess, to a sufficient degree of accuracy, the mean long-term values of R at the lower station over a longer period (1934–1952), as it was done in [4].

Analysis of variations in water and sediment runoff of the Kura River before 1965 was made in [4]. At present, such analysis can hardly be made because of the insufficient initial data. In the late 1980s, the publication of information on the river runoff was ceased. Fortunately, the information on water discharges up to the year 1993 and the information on sediment discharges up to the year 1988 became available for the researchers. The missing values of R over the period of 1989–1993 were approximated using the relationship connecting Q and R over the period of 1974–1988 (it was since 1974 that a new ratio of Q vs R, unlike the previous ratio, was found for the hydrological station of Sal'yany). The results of assessing the variations in water and sediment runoff of the Kura River (at the Sal'yany station) over the entire series of observations are given in Tables 1 and 2 and shown in Fig. 1. The following notations are used in Tables 1 and 2: Q_0, m^3/s is mean long-term water discharge; W_0, km^3/year is mean long-term water runoff; Q_{max} and Q_{min}, m^3/s are mean maximum and minimum annual water discharges; R_0, kg/s is mean long-term suspended sediment discharge; W_R million t/year is mean long-term suspended sediment runoff; s_0, kg/m^3 is mean long-term water turbidity; R_{max}, kg/s is mean maximum annual discharge of suspended sediments.

Two periods can be distinguished in the Kura runoff regime: a nonregulated flow period and beginning in 1953, i.e., after the construction of the Mingechaurskoe Reservoir (654 km from the mouth), a regulated flow period. As follows from Table 1, the regulation and partial withdrawal of the Kura River flow is accompanied

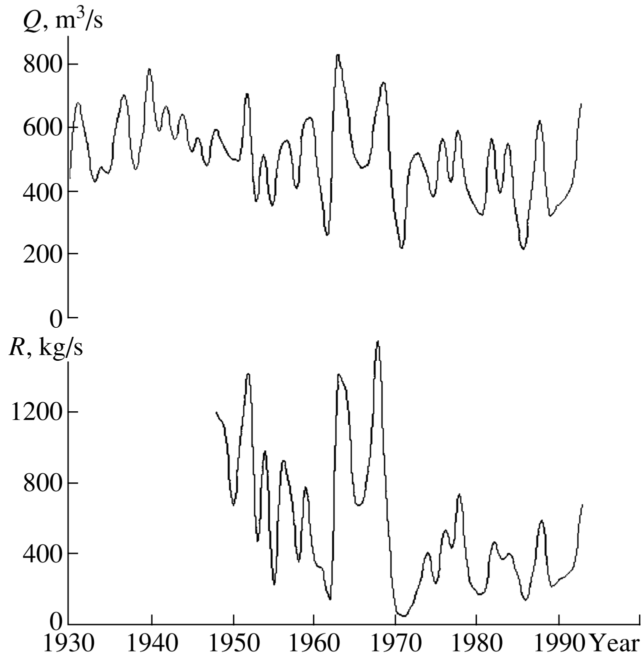

Fig. 1. Long-term variations in the mean annual water and suspended sediment discharges of the Kura River.

by a slight decrease in W_0 (by 3.1 km^3/year or 17.2%), a noticeable decrease in Q_{max} (by 515m^3/s or 31%), and an insufficient increase in Q_{min} (by 18 m^3/s or 12%). The most considerable changes occurred in the runoff W_R, which decreased by 23.9 million t/year or by 60% (Figs. 2, 3). Simultaneously, the water turbidity decreased more than twice.

Changes in the values of Q and R before and after the construction of the Mingechaur Waterworks are well illustrated by Fig. 1. It turned out that the reduction of the annual water runoff began as far back as the 1940s (since 1941) and went on with intervals in the years that followed. However, the values of Q in certain years were rather high. In 1963, the maximum mean annual value of Q (819 m^3/s) over the period of instrumental observations was recorded. Since 1987, a certain increase in Q is observed. After 1952, the sediment runoff decreased even more rapidly and, in some years, the values of R were also rather high; in 1963 and in 1968, in particular, mean annual values of R were maximum over the period of 1948–1993 (1400 and 1600 kg/s, respectively).

In spite of the similarity of long-term variations (to a greater extent, in the character and, to a lesser extent, in the value) of Q and R values at the Sal'yany station, the increase in Q was sometimes accompanied by a decrease in R (for example, in 1957, 1960, and 1969) and vice versa (for example, in 1966, 1974, and 1981). In general, the degree of correlation between the values of Q and R at the Sal'yany station is expressed (over the period of 1953–1988) by the coefficient of correlation of 0.81. Its relatively low value can sometimes be explained by the different charter of correlation between Q and R in various periods of time and even years and by the higher variability of the sediment runoff.

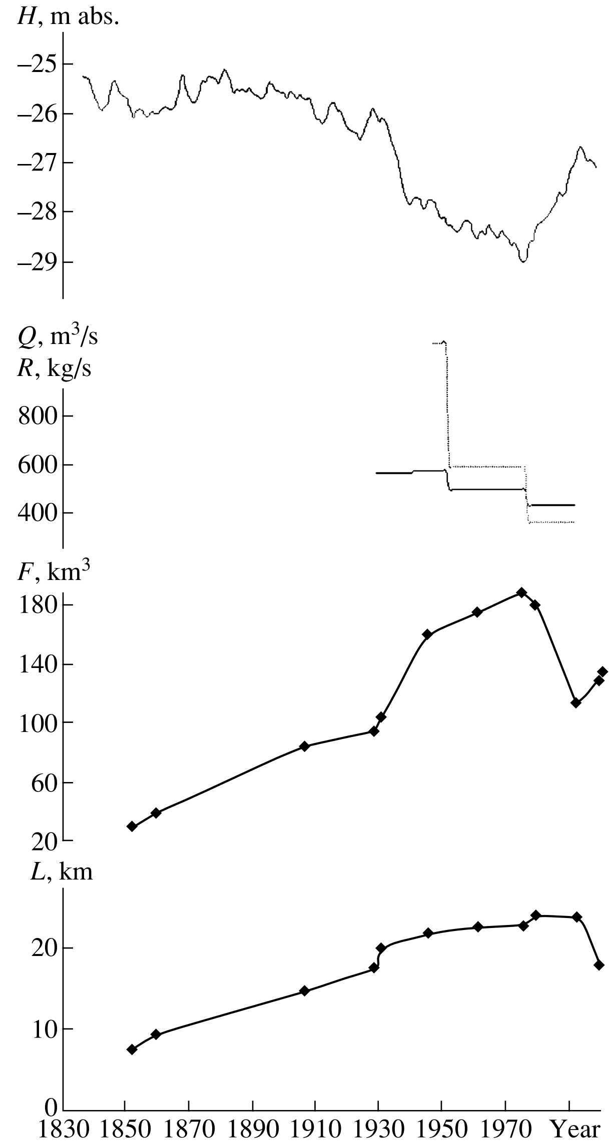

Fig. 2. Long-term fluctuations of the mean annual level of the Caspian Sea H at the town of Makhachkala, mean annual water (solid line) and suspended sediment (broken line) discharges (the hydrological station of Sal'yany) averaged for typical periods, changes in the Kura Delta area and length.

The Kura River flow regulation resulted in the variation of the distribution of water and sediment discharges within a year (Table 3). Before the flow regulation, the high flow period of the year (April–June) accounted for 49 and 73% of the annual runoff of water and sediments, respectively; after the flow regulation, these values dropped to 34 and 60%, respectively. Simultaneously, the shares of the water runoff and sediment runoff increased during the rest low flow period of the year (July–March).

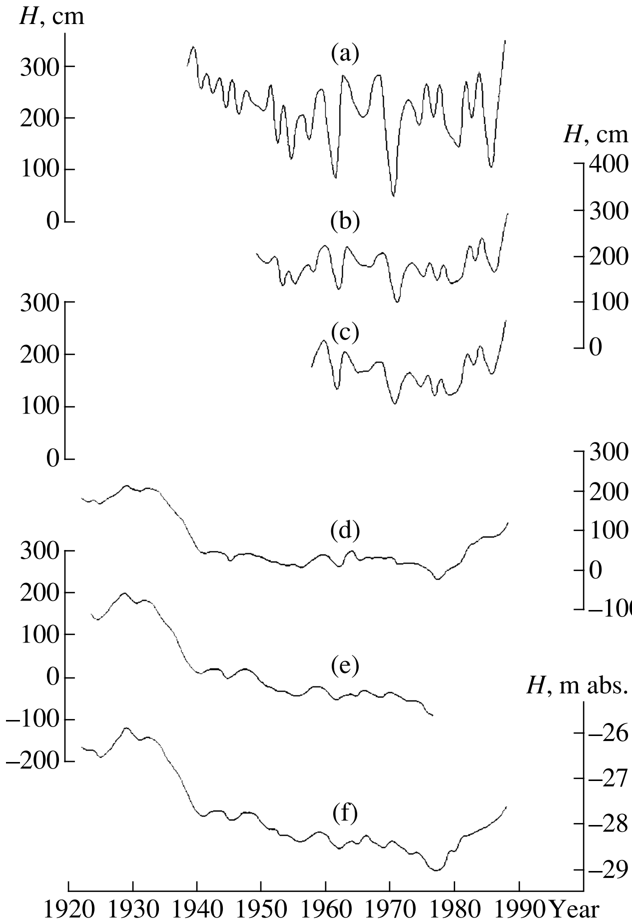

Fig. 3. Long-term fluctuations of the mean annual water levels in the lower reaches of the Kura River (in cm above zero elevation of a hydrological station). (a–f) Hydrological stations of Sal'yany, Karavelli, Severo-Vostochnyi Bank, Ust'e, Zyuidostovyi Kultuk, Makhachkala

The above variations in the regime of Q and R of the Kura River were mainly caused by the impact of the Mingechaurskoe Reservoir (the reservoir parameters: the useful and full storage capacities of 7.4 and 16.1 km^3, respectively; 605 km^2 in area; 70 km long; the backup at the dam being 65 m) and irreversible flow losses.

The irreversible flow losses result from water supply for the reservoir filling (early in the 1950s) and evaporation water losses from the reservoir surface as well as from water withdrawal for different needs and primarily for irrigation. According to the cited literature [15, 16], the Kura River flow losses steadily increased (Table 4). However, the actual flow losses over the period of 1976–1985 turned out to be much lower than the forecasted losses. The Kura River flow losses cited in [12] noticeably exceed the data given in [15, 16]. For example, the losses over the period of 1959–1988 averaged 12.7 km^3/year. Considerable flow losses in the Kura River basin, which were likely overestimated, were not confirmed by the observational data at the Sal'yany hydrological station (these data should by all means take into account all flow losses in the upstream reaches). The analysis of the observation series over the period of 1930–1993 (Table 1, Fig. 1) or over the period of 1959–1988 [12] revealed that the real flow losses in the Kura River basin were probably 3–5 km^3/year. It should be mentioned that, in the last 10–15 years, flow losses could become lower due to the economic production recession; in addition to this, they could be partially compensated by the natural increase in the river flow.

Sea Waves

According to [5, 7], strong north and northeast winds are often observed in the Kura mouth area. These winds with the velocities of 6–10, 11–15, and 16–20 m/s account for 17.2, 8.2, and 2.3%, respectively, of winds of all directions and velocities during a year. These winds cause waves of northern direction in the near-shore area of the Kura River. The height of 5% probability waves in the coastal zone reached 3–4 m. Such winds are responsible for the origination of intense alongshore sediment drift in southern direction [2, 4].

The Caspian Sea Level Fluctuations

Instrumental observations over the Caspian Sea Level were carried out over the period of 1830–2000 [5, 7, 8]. The analysis of the results of these observations (Fig. 2) made it possible to distinguish the following five periods in the sea level fluctuations during the XIX and XX centuries, when the modern Kura Delta was formed: slow sea level drop from the mid-XIX century to 1929 (roughly from –25.5 to –25.9 m abs.); rapid and sharp sea level drop during 1929–1941 (from –25.9 to –27.8 m abs, i.e., by 1.9 m); slow sea level drop during 1941–1977 (from –27.8 to –29.0 m abs., i.e., by 1.2 m); rapid and sharp sea level rise during 1977–1995 (from –29.0 to –26.7 m abs., i.e., by 2.3 m); slow sea level drop from 1995 to 2001 (from –26.7 to –27.2 m abs., i.e., by 0.5 m).

The sea level fluctuations result not only in changes in the Kura Delta area and configuration. They also cause water level variations in the mouth area and, as a consequence, contribute either to erosion of the main river channel, concentration of the river flow in this channel and dying off of lateral water streams (at the sea level drop) or to accumulation of sediments and partial flow rehabilitation in lateral dying water streams (at the sea level rise). Unfortunately, the data on water level fluctuations at hydrological stations in the Kura River are insufficient.

Processing of the available data on water levels (Fig. 3) has revealed the following:

water level fluctuations in the near-shore zone of the Kura River (the hydrological station of Zyuidostovyi Kultuk) virtually coincide with the sea level fluctuations at the town of Makhachkala (Fig. 2);

Table 3. Distribution of water and sediment discharges of the Kura River within a year

Charac-teristics	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Natural regime (1938–1939, 1946–1952)													
*Q**	352/5.3	370/5.6	459/7.0	909/13.8	1350/20.4	992/15.0	466/7.1	217/3.3	265/4.0	420/6.4	427/6.5	370/5.6	550/110
Period of 1948–1952													
*R***	149/1.1	161/1.2	369/2.9	2860/22.2	3600/27.8	2960/22.9	586/4.5	49/0.4	417/3.2	1130/8.8	475/3.7	169/1.3	1080/100
Regulated regime (1953–1988)													
*Q**	518/9.0	530/9.3	535/9.3	636/11.1	727/12.7	603/10.5	345/6.0	286/5.0	321/5.6	347/6.1	389/6.8	495/8.6	478/100
*R***	189/3.0	258/4.1	458/7.4	1150/18.4	1540/24.6	1090/17.4	393/6.3	220/3.5	249/4.0	292/4.7	207/3.3	207/3.3	521/100

* Above line is m^3/s, below line is %.
** Above line is kg/s, below line is %.

during the sea level drop in 1930–1970, the river water level drop was recorded at other hydrological stations; normally, the intensity of the level drop decreased in the upstream reaches of the river. For example, over the period of 1939–1965, mean annual values of the sea level decreased by 0.9 m (Fig. 2). Over the same period, mean annual water levels of the river decreased by 0.7 m (Fig. 3) at the hydrological station of Sal'yany located 85 km from the sea (the data on other hydrological stations are not available). The river water level drop is partially related to fluvial downcutting, that is confirmed by a decline in curves $Q = f(H)$, and partially it is due to flow regulation [4];

the sea level rise during 1980–1990 resulted in backup propagation into the river mouth reach. For example, over the period of 1978–1989 the water level rose by 1.5 m in the sea, by 1.4 m at the hydrological station of Ust'e (2.2 km from the sea), by 1.3 m at the hydrological station of First Mayak (6.8 km from the sea), by 1.2 m at the hydrological station of Severo-Vostochnyi Bank (19 km from the sea), and by 1.0 m at the hydrological station of Karavelli (27 km from the sea). Undoubtedly, the backup, which was caused by the sea level rise and exceeded 2.3 m during 1978–1995, propagated to the river reaches upstream of the hydrological station of Sal'yany.

OLD DELTAS OF THE KURA RIVER

During historic times, the Kura River formed a number of delta lobes, which was favored by the significant river sediment runoff and variations in the Caspian Sea Level. Periodic transgressions and regressions of the Caspian Sea essentially changed the coastline configuration in the area of the present Kura-Araks Lowland. During significant transgressions, this lowland turned into an inland shallow water bay, in which old deltas of the rivers of Kura and Araks were formed. Over the period of large-scale regressions, the delta of the Kura River protruded into the sea far more to the east of the modern delta.

Table 4. Reduction of annual water runoff of the Kura River, km^3/year, under the impact of human activities (here and in Table 6 dash means lack of information)

Time period	According to [15]	According to [16]
1936–1940	0.2	0.2
1941–1950	1.0	1.0
1951–1955	0.7	0.7
1956–1960	1.6	1.6
1961–1965	0.2	0.2
1966–1970	1.2	1.2
1971–1975	3.2	3.2
1976–1980	5.1*	3.5
1981–1985	5.0*	4.0**
1986–1990	6.3*	4.8**
1991–1995	–	6.0**
1996–2000	7.6*	6.8**
2001–2010	–	7.2**

* According to the forecast of 1975.
** According to the forecast of 1985

During the last New Caspian transgression, a series of deltas were first formed in the mouth areas of the Kura and Araks rivers and, then after the confluence of the Araks River with the Kura River, deltas were formed in the Kura mouth. The present Kura-Araks Lowland represents a complex of old deltas of both rivers. The traces of these deltas can be found in the present topography of the lowland.

According to Herodotus, Ptolemy, and Strabo, 2000–2500 years ago, the rivers of Araks and Kura had their own deltas. At that time, the Kura River formed the so-called Mil'sko-Karabakhskaya delta [17]. Succeeding deltas were formed only in the Kura River mouth and staggered with respect to the river channel [6].

Traces of the second delta lobe were found at the center of the Shirvanskaya Steppe. Later on, the Kura River passed round this delta from the right and formed the third Muganskaya delta. Passing around this delta from the left, the Kura River formed a new delta in the southeast of the Shirvani area. This delta was formed during the Recent Caspian time and had peripheral marks of about 22 m abs. and the area of 200–250 km^2 [17]. This delta is represented by the traces of the main channel, i.e., the Kumlavararkh rill.

The more recent (fifth) Khillinskaya delta is outlined by the contour line –25 m abs [17]. More recently, the Kura River rushed southward in the area of Sal'yany and formed three successive secondary deltas in the sea and in the Kyzylagachskii Bay (other names are Akchagyl'skii Bay, Kirov Bay). These deltas were named Sal'yanskie deltas. For a long time, the Akusha channel was observed instead of the easternmost delta; the traces of this channel are still available in present-day maps.

In the late XVIII century, the last of the above-mentioned deltas was observed on the sea coast [6, 17].

As seen from the map prepared under the supervision of A. Nagaev in 1793 (Fig. 4), downstream of the Araks River inflow, the Kura River turns sharply to the south and empties into the Caspian Sea through several branches in the area of the Kura Island (now Kurinskii Kamen' Island) far to the south of the modern delta. The Kurinskaya Spit is yet missing in this map.

The cited map reveals that, firstly, the Kura River outbreak in a new direction and the start of formation of the modern delta of this river date back to the period after 1793 and, secondly, being a product of wave-induced breakdown of one of the Sal'yany deltas, the Kurinskaya Spit is a relatively young formation (this spit began its formation only after the river flow changed its direction).

EVOLUTION OF THE MODERN KURA DELTA

The evolution of the modern Kura Delta was analyzed using the data of nautical charts and topographic maps as well as space images (beginning in 1976). All the charts, maps, and results of surveys were presented in the same projection and were scaled to 1 : 200 000. Layouts of the delta in different years are shown in Fig. 5. Simultaneously, morphometric characteristics of the Kura Delta were defined (Table 5). The following notations are assumed in Table 5: H, m abs. is the sea level; L, km, is the delta length along the main channel; F, km^2 is the delta area; L_{delta} coastline, km, is the delta coastline length; B, km, is the delta width at its base; L is variation of the delta length over the period; F is variation of the delta area over the period. Sea bars separated from the coast and lagoons open in the seaward direction are not included into the delta area. In determining the main channel length and the delta area, the eastern edge of the ridge of sand dunes (the sea coast before the Kura River outbreak in the late XVIII century) was taken as an initial line. This nearly straight line is well seen in maps and runs along the eastern outskirts of the settlements of Neftechal and Bank.

The Kura Delta before the Sea Level Drop in the 1930s

The time of beginning of the modern delta formation during 1800–1810 was approximated using the backward extrapolation of graphs showing the variations in the length of the Kura main channel within the delta and in the delta area (Fig. 2).

The Kura River outbreak through the coastal wave-cut bar and changes in the direction of the river flow into the Caspian Sea could probably occur a little earlier. This event is referred to the late XVIII century in [6, 14]. As follows from the above data and the map (Fig. 4), the outbreak must have likely occurred at the very end of the XVIII century. The high level of the Caspian Sea at that time could promote such outbreak [10, 13]. It is notable that, in the late XVIII century–early XIX century, the modern delta of the Sulak River began its formation after the similar outbreak [10]. Before that event, the Sulak River emptied into the Agrakhanskii Bay.

After the river water flush in a new direction, the entire Kura River runoff was gradually concentrated in a new channel. The formation of the modern delta of the Kura River began. The Sal'yany delta located to the south of the new delta was subjected to the destructive impact of sea waves. Washout products of the Sal'yany delta contributed to the formation of the large Kurinskaya Spit in the southward direction; the spit separated the Kyzylagachskii Bay from the sea.

As seen from the map of A.E. Kolodkin (1816), the Kura River has only one branch emptying into the sea and having no delta lobe [14].

The maps prepared in 1852, 1860 (the map of N. Ivashintsov), 1907, and 1929 (Fig. 5), when the water level made up –25.92, –25.99, –25.70, and –25.88 m abs.,

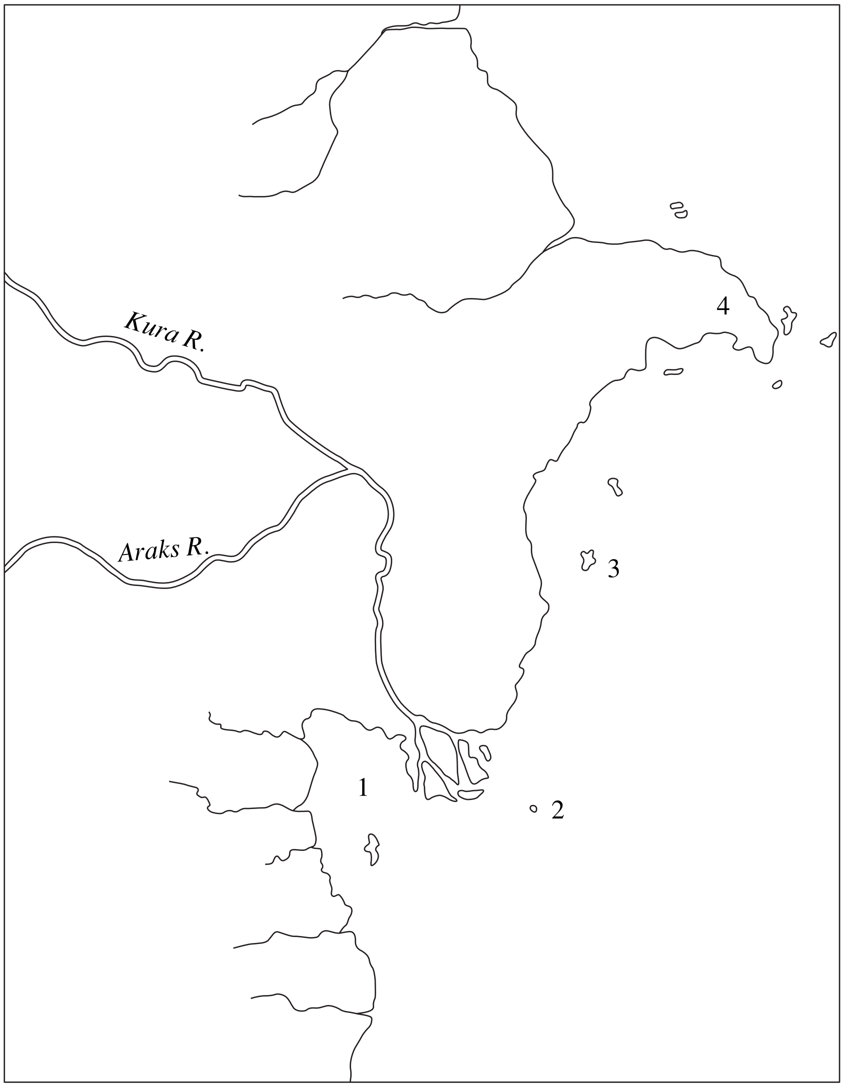

Fig. 4. Drainage system and coastline in the General Map of the Caspian Sea prepared in 1793 and published in 1796. (1) Kyzyltashskii Bay, (2) Kura Isl., (3) Svinoi Isl., (4) Apsheron Pen.

respectively, i.e., it varied insignificantly, illustrated the history of development of the modern Kura Delta.

In 1852, the Kura Delta (Fig. 5) had already two branches, namely, the Northeastern Bank and the Southeastern Bank, which was the main branch. This (southeastern) flow direction in the Kura Delta is still observed at present; under the impact of dominated north and northeastern waves the delta lobe deviated to the south. Later on the Southeastern Bank came to be called Southeastern Branch or the Navigable Kura.

By 1860, the drainage system of the delta changed insignificantly (Fig. 5). However, by 1907 the channel of the mouth part of the Northeastern Bank was divided into two branches; as for the mouth area of the Southeastern Bank, a water stream separated out from it to the left (in the northeastern direction) and again it was called Northeastern (to differentiate these water streams having the same name, the first water stream, which soon died off, was named “bank” and the second was named “branch”). The Northern and North-northeastern branches were formed in the lower reaches of that water stream. The branches of South-southeastern and Asan-Khol separated out from the main Southeastern Bank (branch) to the left.

By 1929, the runoff of the Northeastern Bank drastically decreased, the North-northeastern Branch disappeared.

Over the period of 1852–1929, the delta protruded into the sea by 9.8 km and its area increased by 65 km^2 (Table 5). The intensity of the delta protrusion into the sea gradually decreased with depth (Fig. 2). For example, the rate of the delta area increase dropped from 1.25 km^2/year in 1852–1860 to 0.95 km^2/year in 1860–1907 and then, over the period of 1907–1929, it dropped to 0.45 km^2/year.

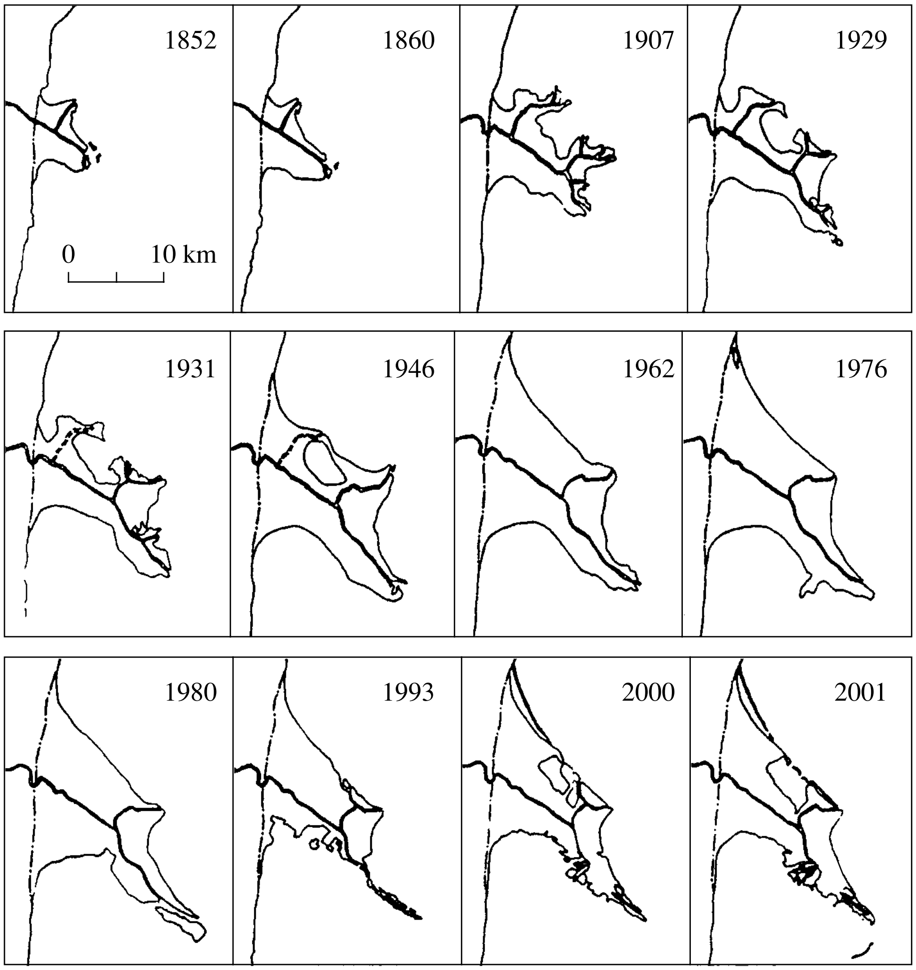

Fig. 5. Dynamics of the Kura Delta over the period of 1852–2001.

By 1929, i.e., by the beginning of the sharp Caspian Sea level drop, the delta of the Kura River was 17.5 km long, its area being 94 km^2 (Table 5).

Transformation of the Kura Delta over the Period of the Caspian Sea Level Drop During the 1930s–1970s

The results of the Kura Delta surveys made in 1931, 1946, 1962, and 1976 reveal considerable changes in the morphological and morphometrical characteristics (Fig. 5, Table 5) under the joint impact of the Caspian Sea level drop and the river sediment runoff decrease.

During 1929–1931, the sea level dropped from –25.88 to –26.16 m abs., i.e., by 0.28 m, and by 1946, it dropped by 1.71 m more. Over the period of 1929–1946, the sea level dropped by nearly 2 m. By 1962 and 1976, the sea level dropped to the elevations of –28.53 and –28.97 m (by 0.66 and 0.44 m, respectively). In 1976, the sea level was only 4 cm higher than in 1977, when it reached the lowest value (–29.01 m abs.) at least over the past 400 years [13].

After 1953, the sediment runoff of the Kura River decreased (Fig. 1). Evidently, this circumstance did not affect the intensity of the delta protrusion into the sea; because, at that time, it mainly depended on the Caspian Sea level drop.

Over the period of 1929–1946, a promontory located in the mouth of the Southeastern Branch protruded into the sea by 4.2 km; the delta area drastically increased from 94 to 161 km^2, by 67 km^2 or by 71%. The delta protrusion was particularly intense and rapid during the first years of the sharp sea level drop: by 1931, the southeastern promontory became longer than it was in 1929 by 2.5 km and increased in area by 10 km^2. The intensity of F increase in that period (5 km^2/year during 1931–1946) was maximum in the history of development of the modern Kura Delta (Table 5); of course, this was primarily related to the sharp sea level drop in that period (Fig. 2) under the condition of the considerable river sediment runoff.

Downcutting of the channels of the Kura River and its main continuation in the delta, i.e., the Southeastern Branch, resulted in dying off of the Northeastern Bank

Table 5. Morphometrical characteristics of the Kura Delta

Year	*H*, m abs.	*L*, km	*F*, km²	*L* delta coastline	*B*, km	Δ*L**	Δ*F***
1852[1]	–25.92	7.7	29	18.8	9.5		
1860[2]	–25.99	9.4	39	22.5	9.3	1.7/0.21	10/1.25
1907[2]	–25.70	14.7	84	51.5	10.8	5.3/0.11	45/0.95
1929[2]	–25.88	17.5	94	54.0	11.7	2.8/0.13	10/0.45
1931[2]	–26.16	20.0	104	71.0	11.7	2.5/1.25	10/5.00
1946[2]	–27.87	21.7	161	56.0	22.0	1.7/0.11	57/3.80
1962[2]	–28.53	22.5	176	56.0	25.3		
1976[3]	–28.97	22.7	189	60.0	25.0	0.8/0.05	15/0.94
1980[4]	–28.57	24.0	180	62.0	25.0	0.2/0.01	13/0.93
1993[5]	–26.96	23.7 14.0[8]	114 111[8]	67.0 50.0[8]	22.5	1.3/0.32	–9/–2.25
2000[6]	–27.10	18[9]	130[10]	63.5	24.0	–0.3/–0.02 –10/–0.77[8]	–66/–5.08 –69/–5.31[8]
2001[7]	–27.21	18[9]	136[10]	62.0	24.0		
						–5.7/–0.81 4.0/0.57[8]	16/2.29 19/2.71[8]
						0/0	6.00/6.00

* Above line is km, below line is km/year.

** Above line is km², below line is km²/year

[1] State topographic and general purpose topographic maps.

[2] Data of navigational surveys cited in [3, 14].

Images from satellites:

[3] Landsat/MSS,

[4] Meteor-Priroda/Fragment

[5] Resurs-F/KATE-200,

[6] Resurs-O/MSU-E,

[7] Terra/ASTER

[8] Morphometrical characteristics given below line do not take into account islands, i.e., natural levees in the inundated part of the Southeastern Branch mouth (Fig. 6).

[9] With regard to the largest channel in the outbreak.

[10] Without regard to the area of bars.

and lateral offsets of the Northeastern Branch (Fig. 5). The downcutting was accompanied by the sea level drop. Dewatering of a cofferdam between fans of these water streams favored the isolation of a large water body within the delta (Lake Yakopinskoe) boundaries.

The tendency for the delta development typical of the previous years was still observed in 1962 (Fig. 5). The delta length and area increased by 0.8 km and 15 km², respectively. The rate of the delta area increase was rather high (0.94 km²/year). The Northeastern Branch (it became to be called the Old Kura) went on dying off. Lake Yakopinskoe got desiccated.

The image made from the Landsat satellite on June 15, 1976 displayed the delta condition at the end of the last regression of the Caspian Sea. Under the condition of the continuing sea level drop the delta protruded to the southeast as before. By 1976, the delta length and area increased as compared to the values observed in 1962 by 0.2 km and 13 km², respectively. Out of 13 km² of the delta increment area, 2 km² were accounted for the surface part of the so-called new delta of the Kura River, which was formed in the mouth of the man-made canal (the Southwestern Branch) cut in 1964 through the right mouth spit in the direction of the hydrological station of Zyuidostovyi Kultuk. Although the canal was in active operation only a few years, an insignificant flow still passed through it. The outflow of turbid Kura water through this canal into the bay is seen in the image made in 1976. Land increment under the condition of the sea level drop was also observed at the northeastern delta coastline, where the coastline protruded in the seaward direction to a distance of 125 m, and at the eastern delta, coastline, where the protrusion reached 200 m. In the latter case, the protrusion was accompanied by flattening of the coastline configuration. By

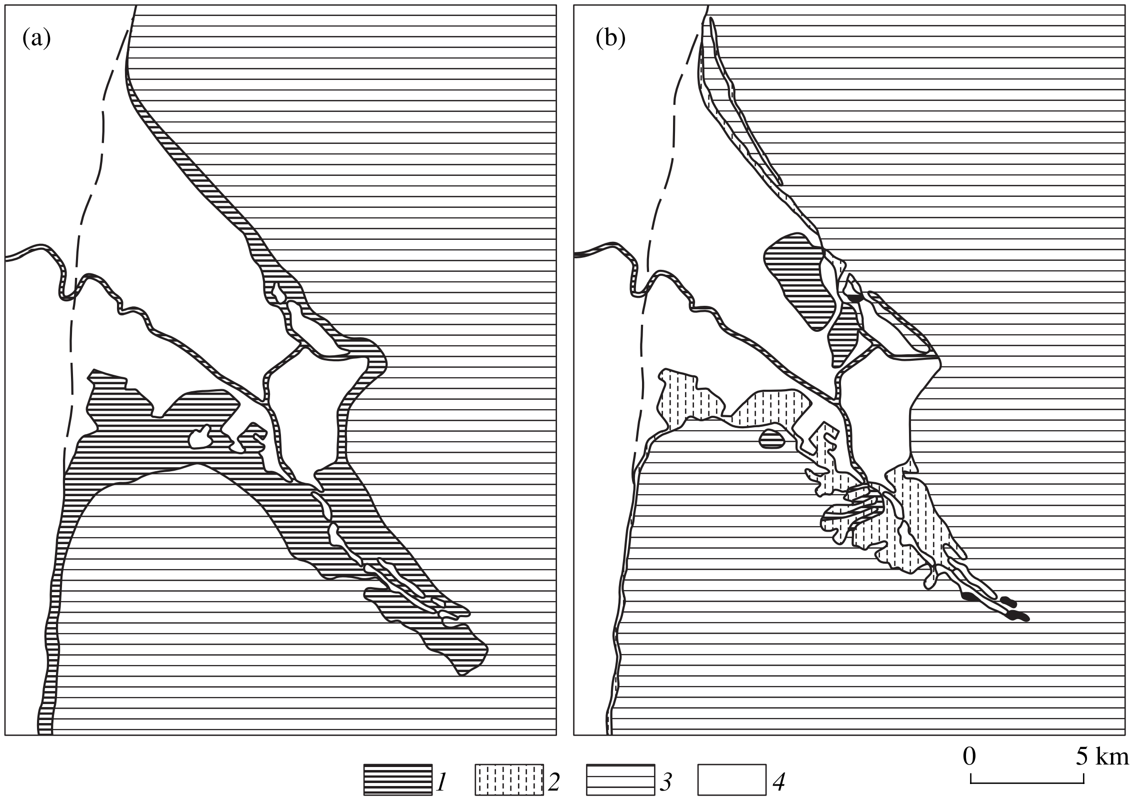

Fig. 6. Changes in the Kura Delta over the periods of 1980–1993 (a) and 1993–2000 (b). (*1*) Land area inundated over the period; (2) Land areas drained after inundation and rehabilitated over the period; (*3*) Sea; (*4*) Land.

1976, the delta area increased up to 189 km^2 (this is the maximum value of the modern Kura Delta area).

Changes in the Kura Delta During the Recent Sharp Rise of the Caspian Sea Level

The delta development over the period of 1978–1995 occurred under the condition of decreased (as compared to the conditions before 1953) river sediment runoff and, which was more important, against the background of a considerable rise in the Caspian Sea level (Fig. 2). After 1977, the sea level increased by 2.35 m and, in 1995, it reached its maximum value over the last 65 years (–26.66 m abs.). The rate of the sea level rise at that period averaged 12.4 cm/year.

The main consequence of the sea level rise was the submergence of low-lying peripheral parts of the delta and reduction of its area (Figs. 2, 5; Table 5).

By 1980, when the survey from the Meteor-30 satellite (using the "Fragment" equipment) was completed, the accumulative processes still dominated in the delta and protrusion of the Southeastern Branch of the delta continued (Figs. 2, 5, 6) in spite of the starting sea level rise, which reached the elevation of –28.57 m (from 1977, the sea level rose by 0.44 m). The delta length increased in this direction by 1.3 km as compared to the value observed in 1976, the delta area at the end of the promontory increased by about 2 km^2. However, the sea level rise caused inundation of land areas in the northeast along the delta coastline up to 1 km wide and part of the delta 2 km^2 in area near the offset of the Southwestern Branch. An alongshore wave-cut bar was formed in a shallow water coastal zone throughout the length of the northeastern delta coastline (a light strip of this bar is well seen at a distance of 1–2 km from the coast in the color synthesized photograph). The formation of wave-cut bars, spits and narrow lagoons between them and the coast (all of them being in parallel with the low-lying alluvial sea coast) is a typical consequence of the sea level rise. Such processes are inherent, for example, in the Caspian Sea coasts in the deltas of the Terek and Sulak rivers and in their vicinity [9, 10].

Any noticeable changes in the southwestern delta coastline caused by the sea level rise have not occurred so far. The joint action of the processes of further accumulation of sediments at the end of the deltaic promontory and inundation of the strand resulted in the delta area reduction by 9 km^2; in 1980, the delta area totaled 180 km^2 (Table 5).

Considerable changes have occurred in the delta by 1993, when the sea level reached the elevation of –26.96 m and was higher by 1.6 m in comparison with the level observed in 1980 (Figs 5, 6, Table 5). The survey carried out in 1993 revealed the delta condition nearly corresponding to the maximum value of the present transgression of the Caspian Sea. The sea level rise caused the inundation of a great portion of the deltaic promontory, which was formed after 1907 and represented a swamp overgrown with reed; the delta length decreased by 10 km against the value observed in 1980. The delta outline lost its natural habit; the delta boundaries acquired the so-called human-induced configuration. Water approached the dikes of a fishery farm in the southeast of the delta; diked agricultural fields and areas prepared for fish hatcheries were inundated in the southwest of the delta. As a consequence, the delta coastline acquired a rectilinear acute configuration. The delta area (excluding islands) considerably decreased (by 69 km^2) against the delta area in 1980 and by 1993 it was 111 km^2. Narrow land strips, which represent former natural levels overgrown with reed, have survived in the inundated part of the deltaic promontory; in addition to this, there are some spoil banks left after dredging on the branch. These land areas formed long islands up to 0.5 km wide, which stretched at a distance of about 10 km to the former right bank of the Southeastern Branch. Similar islands along the left bank of the branch turned out to be narrower. Their strip is discontinued at the base part opening the way for river water flow into the sea. Some portion of river water entered the sea through discontinuities in the chain of islands located along the right bank of the branch. The area of islands amounted to 3 km^2.

Thus, over the period of 1980–1993, the Kura Delta area decreased (with respect to islands along the channel) by 66 km^2 or by 37% as a result of inundation of low-lying delta areas. It is worth mentioning that similar processes caused by the Caspian Sea level rise occurred in the delta of the Sulak River [10]. Over the period of 1978–1997, inundation caused a decrease in the delta area of the Sulak River from 70.6 to 45.1 km^2, i.e., by 25.5 km^2 or by 36%.

Changes in the Kura Delta after 1995

The results of space surveys of 2000 (Figs. 5, 6) made it possible to reveal changes in the delta caused by a slow drop in the Caspian Sea level, which began after 1995. In 1996, 1997, 1998, 1999, 2000, and 2001, mean annual values of the sea level made up –26.80, –26.95, –26.94, –27.00, –27.10, and –27.20 m abs., respectively. Thus, by the year 2001, the Caspian Sea level has dropped by 0.54 m in comparison with the sea level observed in 1995. This had an immediate impact on morphological and morphometrical characteristics of the delta (Figs 5, 6, Table 5).

Shallow water areas of the southeastern edge of the delta promontory, which had been inundated in 1993 as a result of the sea level rise, were partially desiccated and overgrown with reed. The northeastern left-bank part of the deltaic promontory previously inundated, where natural levels did not prevent river sediments from accumulation, was nearly completely rehabilitated, while the southwestern right-bank part was only partially rehabilitated. Diked fields inundated by 1993 were overgrown with reed. As a consequence, the coastline got smoothed and acquired again the natural configuration. The delta area increased by 16 km^2 as compared to the area in 1993 and by 2000, it was equal to 130 km^2.

The year 2000 featured the restructuring of the coastal zone relief throughout the northeastern delta coastline. A complex of bars and lagoons was formed here, which was typical of the coastal zone of the entire western seaboard of the Caspian Sea. The depth increase at the sea level rise resulted in intensification of wave activity and in formation of alongshore bars, which stretched at a distance of 20 km and separated narrow lagoons up to 1 km wide. In addition to this, large lagoons more than 10 km^2 in area were formed within the delta boundaries on the left bank of the Kura River as a result of the water rush into the low-lying part of the delta through the breached section of the longshore bar.

In 2001, the formation of the complex of bars and lagoons went on at the northeastern delta coastline. A longshore bar 12 km long formed between the capes of the Northeastern and Southeastern branches; this bar detached a small lagoon.

Peculiar changes occurred in the drainage system of the delta. In the period of the high sea level, which was probably in 1994 or in 1995, the flow of the Kura water through outbreaks in the chain of islands along the right bank of the Southeastern Branch became more intense. This was likely favored by increased water discharges in the Kura River and by the levels in the mouth area in those years. The water overflow resulted in the formation of an erosional outbreak on the right bank of the branch at the bend 8 km from the branch head and 4 km from the head of the Northeastern Branch. A talus fan of this outbreak and a system of small channels are well seen in the space image made in 2000 (Figs. 5, 6). In 2000, the flow through the continuation of the Southeastern Branch channel is seen in the lower part of it in a 4 km long reach near the former mouth. The outflow of turbid river water from the mouth is not observed.

The space survey carried out in March 2001 (Fig. 7) revealed the evidence of further restructuring of the delta channel network. Evidently, under the condition of the sea level drop the erosion in outbreak channels became intense and the outbreak intercepted the entire flow of the Southeastern Branch. A considerable part of the branch downstream of the outbreak became shallow and was completely overgrown with reed. Water remained only in the vicinity of the branch mouth and the branch mouth proper was dammed by a wave-cut bar. Being elongated by 400 m, the cape of the Southeastern Branch bent to the southwest; the narrow “new Kurinskaya Spit,” which was 3 km long and 100–200 m wide and directed to the southwest, was formed in the

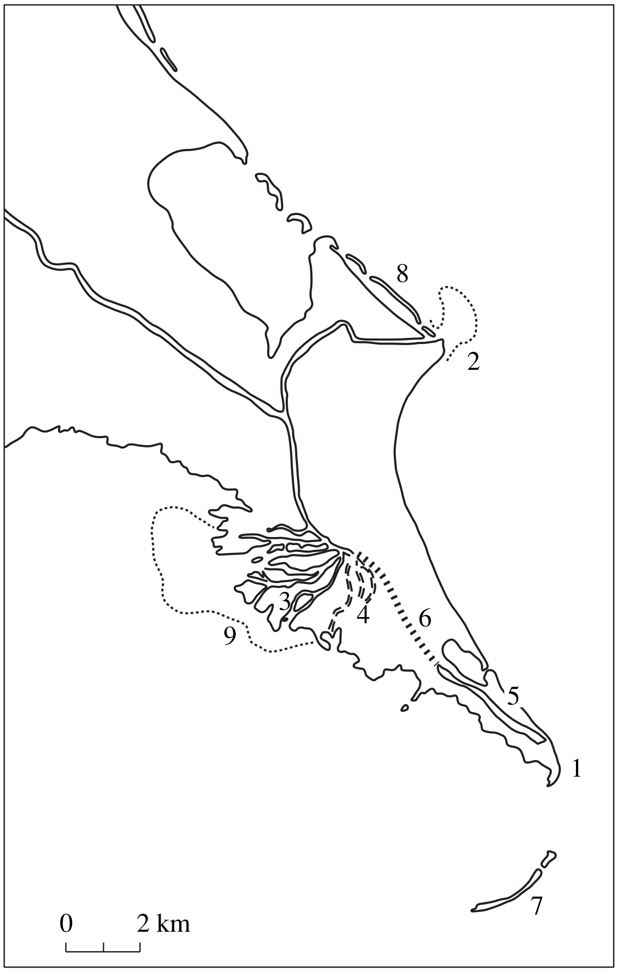

Fig. 7. Layout of marine delta of the Kura River (according to the space image of 2001). (1) Southeastern Branch cape; (2) Northeastern Branch cape; (3) Debries cone of outbreak and channels; (4) Died off channels; (5) Mouth part of the Southeastern Branch channel filled with water; (6) Shoaled part of the channel of this branch; (7) New Kurinskaya Spit; (8) Spit separating the lagoon; (9) Trail of turbid river water.

sea 3 km to the south of the branch mouth. The spit was composed of products of the cape destruction (Fig. 7).

If the outbreak functions in the future, a new delta lobe directed to the southwest or to the south will be formed in this part of the Kura Delta. One branch will be formed in this lobe, the flow of individual channels in the area of the outbreak will be concentrated in the branch. The evidence of disappearance of lateral channels is proved by the image made in 2001 (Fig. 7).

The intensification of wave-induced washout of the promontory in the mouth devoid of water recharge from the Southeastern Branch will result in an increase in the new Kurinskaya Spit dimensions, its elongation, and displacement to the west.

Thus, radical changes have occurred in the Kura Delta in recent years. They are similar to the hydrological and morphological process in the Sulak Delta after the river water rush to the north in 1929 [10]. A new delta lobe was formed after this outbreak and the Sulakskaya Spit was formed out of the products of the old delta lobe.

Table 6. Distribution of water runoff (above line) and sediment runoff (below line) in % between the main branches of the Kura Delta [1, 2, 4, 14]

Time period	Southeastern Branch	Northeastern Branch
1927–1929	60/–	40/–
1931–1932	65/–	35/–
1946–1950	80/–	20/–
1951–1952	80/75	20/25
1953–1965	85/86	15/14
1966–1970	93/95	7/5
1971–1975	94/96	6/4
1976–1980	95/97	5/3

FLOW REDISTRIBUTION BETWEEN DELTA BRANCHES

Transformations of the modern Kura Delta were accompanied by flow redistribution between delta branches (Table 6).

From 1927 until 1980, the share of the water runoff of the Northeastern Branch steadily decreased (from 40 to 5%). The river flow was concentrated in the Southeastern Branch: by 1980, this branch was responsible for up to 95% of water runoff and 97% of sediment runoff of the Kura River. Simultaneously, the flow in lateral branches virtually ceased. The share of water runoff of the Northeastern Branch decreased from 6 to 2% from 1927 to 1932 and by 1946 this branch disappeared [1, 4]. Over the same period, the share of water runoff of the Asan–Khol Branch varied from 5–8% to 0 [1, 4].

In 1965, 34% of the Kura River flow entered the branch of Zyuidostovskii Kultuk through a man-made canal. However, already in 1966 this share decreased to 5%. In 1976, the water flow through the canal was still recorded (a silt debris cone is seen in the image). By the end of the 1970s, this branch died off.

Suspended sediment runoff is distributed between the delta branches roughly in proportion to water runoff (Table 6). However, under the condition of intense dying off of the branch, the share of sediment runoff decreases more rapidly than the share of water runoff.

Unfortunately, the data on distribution of water and sediment runoff of the Kura River between the delta branches are not available after 1980. It may be suggested that the sea level rise favored a certain “revival” of the Northeastern Branch. However, the share of its flow can hardly now exceed 8% of the Kura River flow.

For the time being, it is hard to tell whether the outbreak formed on the right bank of the Southeastern Branch hypothetically in 1994 or 1995 can cause flow redistribution between the branches. Currently, the outflow of the Southeastern Branch into the sea is most likely not observed and the total flow of the branch is emptied into the sea through the outbreak. Further washout of the outbreak may result in erosion in the upper reaches and in complete disappearance of the Northeastern Branch.

CONCLUSIONS

The formation of the modern Kura Delta began on the turn of the XVIII and XIX centuries. Its ensuing evolution is closely related to variations in the river water and sediment runoff, sea waves, and fluctuations of the Caspian Sea level over a period of many years.

Before the 1930s, the delta dimensions (*F* and *L*, L_{delta} coastline) gradually increases and the drainage system became more complicated under the condition of significant changes in the Caspian Sea level. By 1929, the water flow was observed in three branches of the delta, the length of the delta was 17.5 km, its area was 94 km^2.

During the 1930s–1970s, the main changes in morphological and morphometrical characteristics of the Kura delta were recorded. They were caused by the joint effect of the sea level drop (from –25.88 m abs. in 1929 to –29.01 m abs. in 1977) and the river sediment runoff reduction (from 39.7 to 15.8 million ton after 1953, i.e., by 60%). Because the dominating factor was the Caspian Sea regression, the Kura Delta dimensions steadily increased in that time. From 1929 to 1976, the promontory in the mouth of the Southeastern Branch protruded into the sea by 5.2 km, the delta area became 95 km^2 larger, and the length of the delta coastline extended by 6 km. Downcutting of the Kura River channel, which accompanied the sea level drop, resulted in dying of the Northeastern Bank and lateral offsets of the Northeastern Branch.

The principal consequence of the sea level rise during 1978–1995 (by 2.35 m) was the inundation of low-lying peripheral parts of the delta and a decrease in its area by 78 km^2 (1993) as well as the formation of an outbreak on the right bank of the Southeastern Branch.

The slow level drop of the Caspian Sea (by 0.54 m in 2001), which began after 1995, had an immediate effect on morphological and morphometrical characteristics of the delta: the delta area increased by 25 km^2 against the area recorded in 1993 and it amounted to 136 km^2 by 2001; restructuring of the coastal zone relief occurred throughout the northeastern delta coastline, where a complex of bars and lagoons formed.

By 2001, the outbreak intercepted the entire flow of the Southeastern Branch. The wave-induced washout of the promontory in the mouth of this branch caused the formation of a new sea spit directed to the southwest.

In the future, it is quite possible that a delta lobe will be formed in the outbreak area (provided the flow is concentrated in one of the channels), the washout of the promontory in the Southeastern Branch mouth will become more intense, and a new spit will be extended.

The results of the studies carried out may be helpful in determining the trends in variations of morphological and morphometrical characteristics of other river deltas under the condition of the rising level of the World Ocean.

ACNOWLEDGEMENTS

The work was supported by the Russian Foundation for Basic Research, projects no. 01-05-64058 and no. 02-05-64034.

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