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HYDROPHYSICAL PROCESSES

Regularities in the Motion of Water and Sediments at the Mouth of a River of Estuarine-Deltaic Type: Case Study of the Yenisei R.

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Abstract—The main regularities of the motion of water and sediment at the mouths of different types are described. Examples of river mouths of those types are given. The principles of modern classification of river mouths, which takes into account the hydrological processes in mouth zones, are used for zoning the mouth area of the Yenisei R. The main regularities in the interaction of sea and river waters and sediment transport, typical of estuarine-deltaic mouth type, are considered. The parameters that determine the type of water circulation and stratification in an estuary are evaluated. The main attention is paid to studying the mixing of river and sea water at the estuarine-deltaic mouth of the Yenisei and the mechanism of sediment motion at the mouth in the presence of delta under the joint effect of river runoff and tides.

Keywords: estuary, bay, delta, currents, sea and river water interaction, sediment transport
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INTRODUCTION

The interest to studying the motion of sediments at river mouth is still high, mostly because of the high forest density in mouth areas and their considerable changes. Sediment discharge commonly reaches its maximum during spring floods, resulting in considerable transformations of channels at river mouths. For example, in 1981, after the spring flood in the Lena R., the width of the Sardakhskaya Branch decreased more than threefold and the section-averaged depth at Sardakh Isl. Increased by a factor of 3.5 [31]. The urbanization of river mouth areas causes an increase in the share of fine sediment fractions in the channel due to the return industrial waters, treated wastewaters, and surface runoff from agricultural fields. At the mouths, pollutants are being adsorbed on sediment particles, resulting in water quality deterioration. A domain of brackish water forms in the zone of interaction between river and sea waters. The intense flocculation of particles and their precipitation in this domain causes the pollution of bottom sediments and secondary pollution of water. Part of polluted sediments is discharged into the ocean during spring floods. The secondary pollution of the flow at the mouth has an adverse effect on the formation conditions of the specific ecosystem that exists in the brackish waters of the mouth. Active sediment transport at tidal mouths contributes to the drifting of navigation passes. The transformation of delta branches changes their role in the life of the delta and can cause the choice of another branch for navigation. In this study, regularities of water and sediment motion at the mouth of estuarine-deltaic type are considered in the case of Yenisei R. mouth. The estuarine-deltaic type of the mouth is among the most complex for studying, since the motion of water and sediment in it has some features typical of both deltas and estuaries. The formation of estuarine water circulation at Yenisei mouth is studied, and zoning of the mouth area is carried out with the specific features of the hydrological processes at the mouth taken into account.

SEDIMENT MOTION AT RIVER MOUTHS

Sediment transport at river mouths is governed by counteractive factors: on the one hand, a considerable slowing down of river flow, which causes sediment deposition, and, on the other hand, by the interaction of fresh and salt waters, which hampers sediment deposition. The specific features of sediment motion at river mouths, depending on the type of the mouth area, have been studied in many works, in particular [10, 16, 21, 24, 27]. The comparison of the hydrological regime of the mouths of different rivers and the generalization of data on the characteristic features of water and sediment motion at the mouths require their classification [13]. To identify regularities in sediment transport at different river mouths, we will use the modern classification of mouth types, which takes into account the hydrological processes at river mouths [22]. According to this classification, all mouths are divided into 5 types: simple, estuarine, estuarine-deltaic, deltaic-estuarine, and deltaic. Table 1 gives examples of rivers with mouths of the latter four types

River basin area F and mean annual runoff of water W_Q and sediment W_S at the mouths of rivers of different types

Mouth type	Source	River	F, km^2	W_Q, km^3/year	$W_S \times 10^6$ t/year
Deltaic	[25]	Northern Dvina	357	108	4.4
	–	Pechora	322	130	8.5
	–	Pur	112	32.3	0.6
	–	Taz	150	43.4	0.9
	–	Olenek	219	36.1	1.2
	–	Lena	2490	528	20.0
	–	Yana	238	31.9	4.2
	–	Indigirka	360	54.0	11.9
	–	Kolyma	647	118	12.3
	[29]	Mackenzie	1800	350	130
Estuarin–deltaic	[25]	Ob	2990	402	13.0
	[25]	Yenisei	2580	597	4.9
	[38]	Congo	3700	1350	55
	[36]	Parana, (Rio de la Plata)	2800	670	57
	[15]	Senegal	400	20	2.2
	[28]	Elba	173	26.8	7.8
	[16]	Loire	115	24.8	0.8
Deltaic–estuarine	[23]	Amazon	6500	7280	900
	[27]	Yangtze	1808	888	471
	[26]	Ganges and Brahmaputra	1621	388	479
Estuarine	[25]	Mezen	78	24.4	0.8
	[7]	Tsyantan	56	31.5	2.0
	[10]	Saint Lawrence	1300	379	5.5
	[9]	Delaware	34	10.6	1.7

and their major characteristics: river basin area F, mean water runoff W_Q, and sediment runoff W_S. Since the motion of sediments, their passage into suspended state, and precipitation depend on flow velocity and water dynamics at river mouth, we will briefly discuss the specific features of water dynamics in different types of mouths.

Specific Features of Water and Sediment Dynamics in Different Types of Mouths

Typical features of deltas are the gentle slope of the delta plain, weak intrusion of seawater into delta branches, the formation of sand bar, and frequent countercurrents, associated with wind setups. Many researchers subdivide the deltaic type of mouth into bayhead deltas (forming in bays and estuaries) and protruding deltas (on open coasts). A mouth area with a filling delta, which forms in an estuary in accordance with classification [22], refers to estuarine-deltaic type (Yenisei mouth is an example).

The main mechanism of sediment transport in deltas is due to the slowing down of flow in delta branches at their emptying into the ocean. In addition, the vertical heterogeneity of water density at the delta coastline, which is due to the interaction of river and sea water, contributes much to this process. The gradual decrease in flow velocity toward the ocean causes the sorting of sediment along branch channels: coarse sediments (gravel, pebble) deposit near delta head, followed by the deposition of coarse and fine sand, and, finally, clay and silt deposit at the delta coastline. Thus, the delta filters river sediments, resulting in that the sediment that reaches the boundary between protruding delta and the ocean is fine sand and silt, which can mix with marine deposits. At the estuarine-deltaic mouth, part of sediments filtered by bayhead delta enters the estuary where it is transported in accordance with the laws of estuarine circulation. The deltaic-estuarine mouth is a delta in which some branches have funnel-type extensions of their channels, in which the motion of water and sediments follows the laws of estuarine type of mouth. Mouths of this type can be seen in the rivers of Yangtze [7, 27], Amazon [23], Senegal [15], and the Hoogly branch in the mouth area of the Ganges and Brahmaputra [7, 26].

The motion of sediments in estuaries takes place under the effect of estuarine water circulation, which mostly depends on the discharge of river water, tides, and wind. The motion of suspended sediment has some features, one of which is the accumulation of sediments in some reach of the estuary [9, 10, 21, 22]. The dynamics of sediments in estuaries features the formation of a zone of maximal water turbidity (MT) with the concentration of suspended sediment C an order of magnitude higher than that in river and sea waters; this zone forms near the section of maximal propagation of brackish waters at the bed, the velocity of the bottom flow at this section being zero (zero point). The zero point, along with MT zone, migrates upstream and downstream along the channel, depending on changes in river flow, tidal phase, and the spring–neap cycle. This is accompanied by changes in the length of MT zone and the value of C in this zone, the formation of zones of erosion and accumulation of sediments, and sorting of sediments by their size at their deposition sites.

Water circulation in the estuary determines the formation mechanism of MT zone. During high tide, freshwater flow moves seaward at the surface in the estuary, while the flow of brackish water moves near the bed in the opposite direction. The river flow, which slows down while approaching the sea, loses sediments, part of which is captured by the bottom flow of higher density water. This is the first way of sediment entering the bottom flow. Tidal currents are the main generator of flow turbulence in estuaries, contributing to periodic roiling of sediments in tidal estuaries. At the moment when the tidal currents reverses, the heaviest particles settle onto the bed. Part of them is roiled during the low tide as the seaward current velocity increases. This is the second way of sediment particles entering the bottom current. During the high-tide phase, the bottom flow of brackish water with high carrying capacity transports sediments it contains toward estuary head. As it slows down, the bottom flow also loses sediments, which accumulate downstream of the penetration boundary of brackish bottom flow. This is the deposition area of finest sediment fractions from MT zone, which reaches the zero point at the high-tide phase [9, 10, 24]. During low tide, the flow in the estuary becomes unidirectional and suspended sediment moves downstream, gradually depositing as the flow slows down.

The degree of stratification and the mixing of fresh and sea waters in a tidal estuary depend on the proportions of river water volume W, which enters the estuary within a high-tide cycle, and the tidal prism volume P [8]. Simmons criterion $\alpha = W/P$, which is used to determine the type of vertical mixing of river and sea waters in the estuary, allows assessing the vertical stratification of water, averaged over the estuary.

WATER DYNAMICS AND SEDIMENT TRANSPORT AT THE YENISEI MOUTH

Zoning of the Mouth Area of the Yenisei

Unification of the names of individual parts of mouth areas is of importance for the comparison of different mouths, studying and simulating of physical processes, and the establishment of general regularities in the processes that takes place at the mouths of different types [13]. In accordance with the zoning of a river mouth area, taking into account the hydrological processes in the area [22], the estuarine–deltaic mouth of the river is divided into river mouth area, bayhead delta, estuary, and open nearshore area (oceanic coastal zone). Figure 1a gives a scheme of zoning of Yenisei mouth area with distances from its head to the boundaries of the nearshore zone according to data of [4, 6, 14, 19, 25, 30, 39]. High surges during low-water seasons reach the inflow of the right tributary, the Lower Tunguska R. (Turukhansk T., 869 km from the delta coastline (DC)), which is assumed to be the head of the mouth area [25], while tidal level variations reach Igarka gauge (Fig. 1a). The delta head (branching point) lies at the Ust'-Port Settlement (Fig. 1b), where the Malyi Yenisei branch separates leftward. The mouth section of the river also lies here. The delta coastline is situated at the Brekhovskie Shoals, i.e., the Yenisei delta lies between the parallels of 69.40° and 71.00° N.

The head of the estuary will be defined based on the penetration distance of brackish water with salinity $S = 1‰$ into delta branches at the bed during a high spring tide [22]. The propagation boundary of water with isohaline of 1‰ is difficult to establish, because different authors give discordant data obtained in different years [6, 30, 35]. In the opinion of the authors of [6], brackish water in summer and autumn generally do not rise higher than the Sopochnaya Karga Cape. On the other hand, the authors of [30], believe that, according to data of 1982, brackish waters in the bottom flow reach Karaul Settl. Again, the authors of [35] give data of S measurements (summer of 2000), showing that brackish waters in summer and autumn propagate in the bottom layer over more than 400 km from the mouth section, i.e., they reach Baikalovo Settl. Thus, the propagation limit of brackish waters into the estuary during winter low-water period lies at the section at Karaul Settl., which can be taken as the estuary head.

Defining the mouth section of the estuary (EM) by geomorphological characteristics, we assume that it passes from Dikson Isl. in the east along the northwestern coast of Sibiryakova Isl. to Olenii Isl. in the west [14, 30], while the length of the estuary is ~513 km. The width of the nearshore area is determined by the propagation distance of the freshening plume of the Yenisei into the sea. In the sea area adjacent to Yenisei estuary, the salinity of the surface water layer is low, varying from 13 to 28‰ at 74.5° and 76° N, respectively

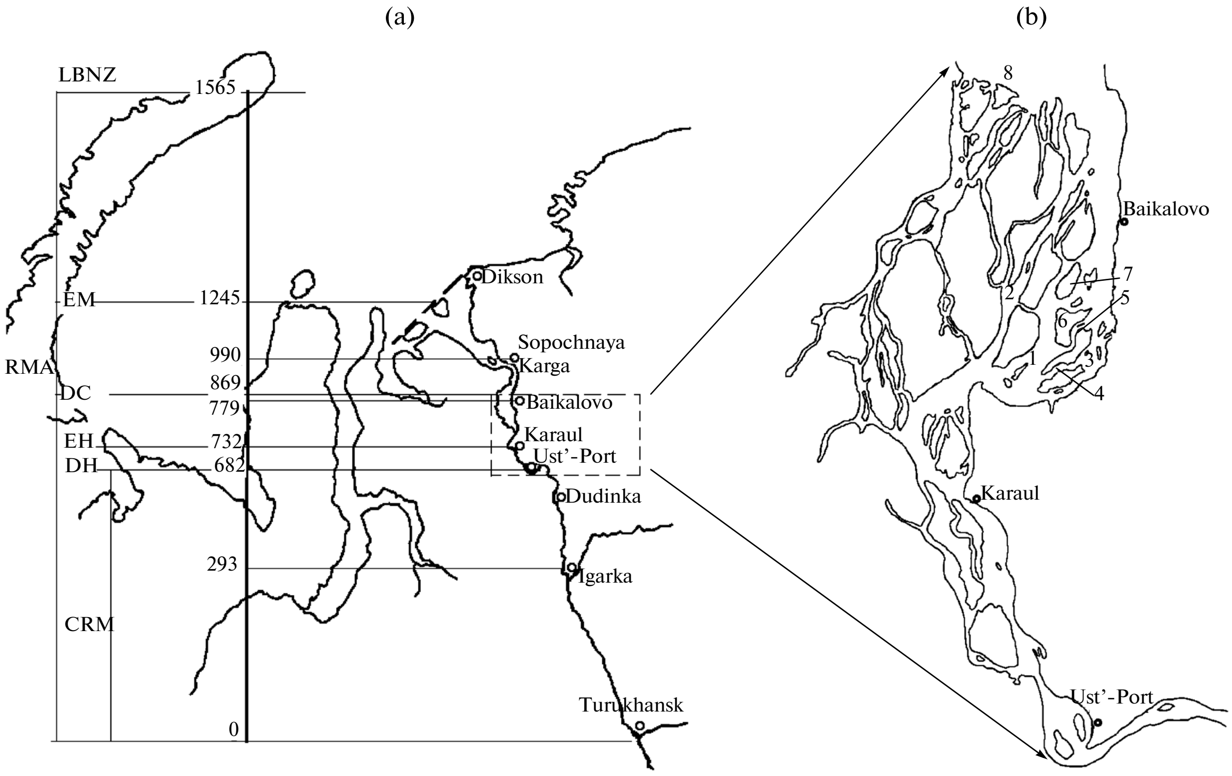

Fig. 1. Schematic map of (a) Yenisei mouth area (RMA) and (b) its estuary with a bayhead delta: (1) Bol'shoi Yenisei, (2) Malyi Yenisei, (3) Kamennyi Yenisei; branches (4) Sudnaya, (5) Chayashnaya; (6) Vasil'evskii Isl.; (7) Turushinskii rift; (8) Brekhovskie shoals. The distances in Fig. 1a are measured from the Lower Tunguska inflow into the Yenisei, km; LBNZ is lower boundary of nearshore zone.

[2, 11, 34]. In the southern parts of the sea, the salinity of the surface water layer shows clear seasonal variations: it decreases in June–September (0–5‰) and increases in other seasons. The coastal zone of the sea features a distinct two-layer structure and estuarine water circulation. With the boundary of the nearshore estuarine area determined by the criterion of surface water salinity: $S = 90\%\ S_0$ (S_0 is seawater salinity) [22], measurement data yield the position of 30‰ isohaline during spring flood reaching 77° N and 200-m isobath (~322 km from estuary mouth section); this distance can be taken as the width of the nearshore mouth zone (Fig. 1a).

The Composition of Sediments in Yenisei Delta Branches

The sediments in Yenisei delta branches are represented by different fractions from pebble and gravel (with diameter varying within 10–100 mm, 1–10 mm) to sand (0.1–1.0 mm), aleurite (0.01–0.1 mm), silt (0.001–0.01 mm), and clay (<0.001 mm) [1, 18]. The coarsest deposits—gravel and pebble occur at bedrock outcrops or bank erosion [1]. On the average, the size of deposits decreases from delta head downstream the branches [18], though detail analysis of the composition of delta sediments [1] shows that the regular decrease in the mean diameter of predominant deposits is not universal in the delta branches. The Bol'shoi Yenisei on the average shows a tendency toward a decrease in sand size from branch source to its mouth. At the source, d is 0.060–0.75 mm, and farther it decreases to 0.27 mm near Cape Muksuninskii, 0.18–0.13 mm near Isl. Vasil'evskii. However, near Turushinskii rift, the size of bottom sediments increases again, and coarse sand with gravel appears in the channel [1]. In the Kamennyi Yenisei, the general regularity of a downstream decrease in the size of sediments is also violated, their size increases downstream until the confluence with the Bol'shoi Yenisei, where coarse sand occupies 90% of branch channel area, while, at the source of the branch, they occupy an insignificant part of its area, which is mostly covered by aleurites and silts. Pebble and gravel on the bed of the Kamennyi Yenisei are due to bedrock outcrops in the channel. Aleurite and silt dominate (up to 70% of the area) in the channels of smaller branches (the branches of Chayashnaya and Sudnaya) [1, 18], the Sudnaya branch showing the minimal diameter ($d = 0.07$ mm) of silt deposits.

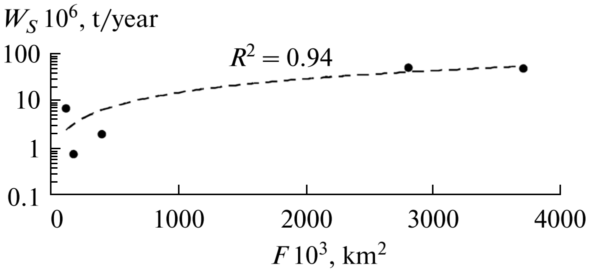

Fig. 2. Dependence $W_S = f(F)$ at river mouths of estuarine–deltaic type.

The Effect of Yenisei Runoff Regulation on Water Discharge and Sediment Runoff at the Head of the Mouth Domain

The mean many-year value of discharge Q_0 of the Yenisei in period 1936–2008, according to [11], is 18700 m^3/s, the mean Q during flood and dry season is 80989 and 5584 m^3/s. The commissioning of the Krasnoyarsk HPS (1972) was followed by runoff redistribution: the maximal Q increased from 80853 to 81137 m^3/s, attained, as before, in June, while the minimal Q increased from 4020 to 7213 m^3/s. Until the start of water flow regulation, the minimal dry-season Q was recorded in April; while after HPS commissioning, the minimal dry-season Q can be recorded from November to April. The start of water runoff regulation caused an appropriate change in the suspended sediment discharge at Igarka gauge. Thus, under natural conditions, the mean water turbidity $\overline{C}$ in the Yenisei R. was 22 g/m^3 (with a maximum during spring flood of 60–90 g/m^3) [25]. HPS operation caused a decrease in both suspended sediment runoff (from 13 to 4.9 million t/year) and $\overline{C}$ (8 g/m^3). In the 1980s, suspended sediment runoff started increasing again, and the value of $\overline{C}$ reached 11 g/m^3.

Mean Sediment Runoff and Seasonal Variations of Water Level and Sediment Transport at the Mouth

The runoff of sediments delivered by the river to its mouth is governed by many factors, the major of those being watershed area, the topography and geological structure of the basin, climate, precipitation, and the extent of the use of water energy lands in the river basin by people. As can be seen from the table, the dependence of sediment runoff on the basin area $W_S \sim \ln F$ holds with approximation reliability $R^2 = 0.9$. Sediment runoff in the Mackenzie delta (though it is situated in permafrost zone, as well as the mouths of the Russian rivers under consideration) is 10 times greater than W_S of Siberian rivers. The involvement of the values of W_S for Mackenzie delta and the mouths of estuarine-deltaic type of the Ob and Yenisei in the study of dependences $W_S = f(F)$ and $W_S = f(W_Q)$ failed to give significant relationships, though those mouths are situated under similar climatic conditions. The relatively large sediment runoff in the Mackenzie seems to be due to the geological structure of river valley [32]. The small value of W_S in the Ob and Yenisei is mostly due to the erosion–accumulative processes in their watersheds; some contribution is also due to the mechanism of sediment transport and accumulation in estuarine–deltaic mouths.

The comparison of mean annual sediment runoff values W_S at estuarine–deltaic mouths of the Yenisei, Ob, Parana (La Plata), Congo, Senegal, Loire, and Elbe shows that W_S for the latter five rivers increases linearly with increasing drainage area F with a reliability coefficient of 0.94 (table; Fig. 2). This conclusion is confirmed by the linear dependence $W_S = f(F)$, obtained in [36] for ~50 rivers all over the world. With the Ob and Yenisei taken into account, it becomes impossible to obtain any reliable relationship. The relatively small W_S of the Ob is due to the boggy and plain landscape of the basin, and that of the Yenisei is due to the presence of rocks on the watershed and river runoff regulation. Some contribution to the decrease of sediment runoff of those rivers seems to be due to permafrost, in the zone of which the Ob and Yenisei are situated, and, according to the authors of [33], the abundance of forests in river valleys.

The fact that the mouth zone and the major portion of the Yenisei R. lie in the permafrost zone plays a significant role in the formation of flow structure and the motion of sediments at the mouth [11]. On the shores of the Yenisei Bay, permafrost brows extend into the bottom water layer, where they are overlain by cooled (<0°C) seasonally frozen rocks. Soil cementation by ice leads, on the one hand, to their greater tolerance to scouring and, on the other hand, to the development of thermokarst and thermal erosion [17]. The properties of permafrost soils have a significant effect on sediment transport in river mouths. During spring flood, bottom sediments have not enough time to thaw, hence they do not move. Seasonal thawing is still not active here, and the import of sediments from nearby territories in river flow is very small. Thus, the concentration of sediments C in river flow in permafrost zone is on the average less than in other regions. As mentioned above, $\overline{C}$ in the Yenisei R. at Igarka Town under natural conditions was 22 g/m^3, and 15 years after the commissioning of the Krasnoyarsk HPS reached 11 g/m^3. The evaluation of $\overline{C}$ in the estuarine–deltaic mouth of the Congo R., according to [38], yields ~40 g/m^3. In the permafrost zone of Saint Lawrence R. estuary, $\overline{C}$ varies from 40 to 80 g/m^3, reaching its maximal value (200–400 g/m^3) during high tide, and sediments are mostly represented by silts and clay particles [10]. Thus, the absence of permafrost rocks in river basin and bayhead delta in the upper part of the estuary facilitates an increase in $\overline{C}$ at the mouth.

Seasonal variations of river water flow are among the major factors affecting hydrological processes at the mouth. During floods, the hydrological regime of the Yenisei mouth determines the large water discharge at Igarka gauge; the maximal mean monthly $Q = 119000$ m^3/s was recorded in June 1959. During the passage of a flood, the major portion of Q reaching delta head concentrates in nearly equal parts in two branches of the Bol'shoi Yenisei (70%) and more than 20% enters the Malyi Yenisei [12]. The further distribution of runoff among delta branches is determined by the morphometry and roughness of branch channel and its position relative to the dynamic axis of the main flow. With a decrease in Q, the share of water in the major branches decreases in favor of lateral branches. The calculation of suspended sediment runoff R and delta head, according to data in [12], at $Q = 70000$ m^3/s, is 1600 kg/s, while at $Q = 9340$ m^3/s, it is 54 kg/s. At the same time, the discharge of suspended sediment R entering the source of the left branch of the Bol'shoi Yenisei during spring flood is twice as large as that for the right branch, the water discharges being similar; this is due to the larger longitudinal slope of the water surface. During the dry season, the distribution of R values over branches corresponds to the distribution of water discharges. During spring flood, the branches Sudnaya and Chayashnaya takes from the Bol'shoi Yenisei up to 65% of its sediment runoff W_S, part of which is involved in the formation of spits at their mouths [12].

The Mixing of Fresh and Brackish Waters at Yenisei Mouth

The evaluation of Simmons parameter α with the use of new data on estuary area: $F_{\text{est}} = 12700$ km^2 [19], taking into account the position of the estuary, determined above, yields $\alpha \sim 0.06$, which lies within the range $0.005 < \alpha < 0.1$. In this calculation, the maximal value of semidiurnal tides at Yenisei mouth was taken equal to 0.5 m [6]. This means that partial mixing of river and sea waters with moderate stratification predominates in the Yenisei estuary. The criterion α is evaluated by the mean characteristics and can be used to assess the vertical water mixing averaged over the entire estuary [9]. It is known that different types of estuarine circulation can form in the same estuary at fluctuations of water discharge in the river [8, 9]. In the Yenisei, the maximal Q during spring flood can be 6 times greater than Q_0 (for example, in June 1959, $Q = 119000$ m^3/s), and the flow in the estuary in this period becomes strongly stratified.

The value of the parameter of water stratification in the estuary $n = \Delta S/S_{\text{av}}$ ($\Delta S = S_{\text{bed}} - S_{\text{surf}}$, $S_{\text{av}} = 0.5(S_{\text{bed}} + S_{\text{surf}})$, S_{bed}, S_{surf} is water salinity at the bed and on the surface, respectively), is a more informative characteristic of water stratification in different parts of the estuary. Parameter n, evaluated by normal annual values of S_{bed} and S_{surf}, given in [35], for the reach between Sopochnaya Karga Cape and the mouth section of the estuary varies within the range 1.2–1.85, thus suggesting a strong water stratification in this part of the estuary (Fig. 3).

The results of calculation of n by isohalines obtained in August 2000 [35] at the reach between the mouth section of the estuary and Baikalovo Settl. are given in Fig. 4. The mean monthly water discharge in this period is $Q = 16230$ m^3/s $<Q_0$; the value of n increases, reaching 1.1 at a distance of 160 km from the mouth. With an abrupt increase in the depth of flow and a decrease in channel width near Sopochnaya Karga Cape (Fig. 5), parameter n decreases to ~0.1 and the flow is almost not stratified. With an increase in the depth in the upstream direction, the stratification parameter increases again (to 1.7) and remains greater than 1 up to the end of the segment of measurements at Baikalovo Settl., thus suggesting a strong stratification of the flow.

The horizontal transitional zone between the fresh and brackish water in the summer lies in the middle part of the estuary between 71°30′ and 72°00′ N. The mean many-year salinity values at the bed in point 71°24′ vary from 8 to 18‰. Those values in some years are in excess of the measured salinity values in summer (August, September), suggesting a possible southward shift of the boundary between the river and slightly saline water in winter. Therefore, the data of measurement of water salinity profiles in Yenisei estuary demonstrated a distinct two-layer structure of water masses.

The results of measurements of flow velocity at Yenisei mouth are indicative of the formation of classical estuarine circulation, which can be easily disturbed by surges, which have a dominating effect on water dynamics in the estuary. The mean velocity of the discharge current in the reach Ust'-Port Settl.—Baikalovo in July—August is 0.3 m/s, and the current is directed seaward [6]. The velocity of the reverse current in the bottom layer varies from 0.2 m/s at Ust'-Port Settl. to 0.3 m/s in delta branches in the reach Karaul Settl.—Baikalovo. In winter, the furthest upstream station, at which reverse current with a velocity of 0.2 m/s was recorded at the bed, is also Karaul Settl. [5]. Thus, the formation of a MT zone can be expected to take place downstream of this section. During setup-induced variations of water level and the passage of long waves into the mouth, the flow becomes unidirectional, and its velocity can remain zero within several hours (for example, at a gage at Ust'-Port settlement (Selyakino gauge) [5]), thus facilitating the deposition of sediments in the reach were flow velocity is zero.

The Effect of Estuarine Circulation and Tides on Sediment Motion at Yenisei Mouth

Variation of the vertical profiles of suspended sediment concentration along Yenisei estuary (Fig. 5,

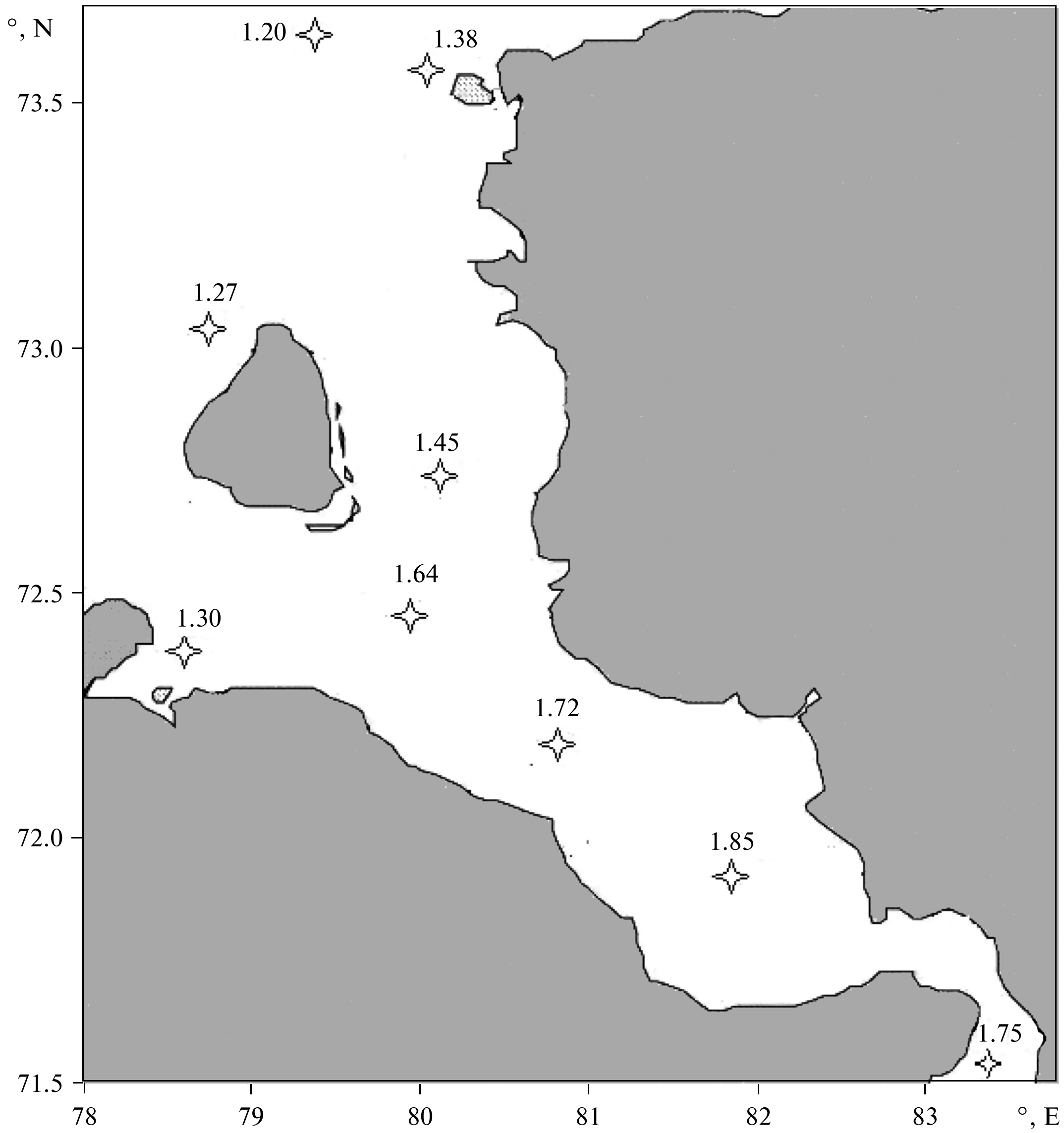

Fig. 3. Changes in stratification parameter *n*, ‰ (digits on the map), evaluated by normal annual values of S_{bed} and S_{surf} [35] in a reach between the estuary mouth section and Sopochnaya Karga Cape.

[34]) shows that, first, water turbidity at the Yenisei mouth in the summer–autumn low-water period is relatively low, and, second, two zones of maximal turbidity form in the estuary within the measurement reach. Of great importance in the formation of both those zones is the structure of the profile of estuary bed. The MT zone closest to the mouth section forms downstream of Sopochnaya Karga Cape in the zone of narrower estuary and an abrupt rise of the bed (Fig. 5). Sediment deposits here from a seaward flow because of its abrupt widening and an ensuing abrupt decrease in flow velocity. The results of measuring the flux of the settling matter [20] confirm the existence of a domain of higher turbidity near Sopochnaya Karga Cape, where the flux of settling material (organic matter, clay, silt), averaged over four tidal cycles is ~200 times greater than such flux near the estuary mouth section (73°00.10′ N, 79°55.61′ E). Those deposits participate in the formation of Yakovlevskaya Spit at the right shore of the estuary downstream of the delta coastline [3]. The abrupt change in bed profile contributes to the formation of two MT zones in the estuary. Thus, in the estuary of the Hudson R. (without filling delta), two MT zone are also forming [37]: one, as well as in Yenisei estuary, forms near the mouth section at an abrupt decrease in the depth, while the other forms 40 km upstream, confined to the intrusion boundary of bayhead water into the estuary and caused by the formation of estuarine circulation. At the same time, with an abrupt increase in the depth (tenfold) between the middle and lower estuaries of the St. Lawrence R. (also without bayhead delta), the second zone of MT

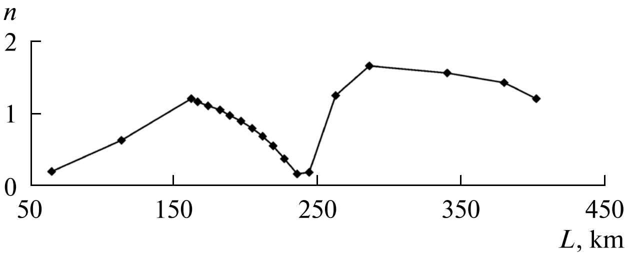

Fig. 4. Variations in stratification parameter n calculated by the values of S_{bed} and S_{surf}, measured in the summer of 2000 [35] in a reach between estuary mouth area and Baikalovo Settl. Here and in Fig. 5, the distance L is measured from EM.

of suspended sediments does not form because of the formation of specific water circulation, accompanied by internal waves, and many-layer flow structure of a very deep lower estuary (~300 m) [10]. Water turbidity in the lower estuary is low. In the top layer down to the depth of 50 m, of which surface water circulation is typical, C is 0.10–2.9 g/m^3; in the middle layer, it is 0.05–0.1 g/m^3; and in the bottom layer, 0.1–0.4 g/m^3. Suspended sediment runoff decreases toward the ocean.

The upstream MT zone forms in a section of extension of Yenisei estuary ~50 km in length (at a distance of 280–338 km from EM) downstream of delta coastline and far downstream of the boundary of maximal penetration of brackish waters into the estuary (Karaul Settl.). However, during summer low-water period, brackish waters, as a rule, penetrate into Yenisei estuary over a distance of 260–380 km from the mouth section, i.e., this MT zone forms near the boundary of brackish water intrusion into the estuary under the effect of estuarine circulation and an increase in the depth and width of the estuary. In this area, deposition and secondary roiling of sediments is taking place, as can be seen from the propagation of a zone of higher water turbidity in the estuary up to the flow surface (Fig. 5). Part of suspended sediment of this MT zone deposits near delta coastline, forming a shallow bar here [25]. No data on the value of C in Yenisei delta branches are available, but perhaps some fine sediments are transported upstream into delta branches during surges and when brackish water penetrates up to the limit of its propagation, with deposition of those sediments in the upper parts of the branches. An indirect corroboration of this is the inverse distribution of d values of the sediments from the sources of the Kamennyi Yenisei branch toward its mouth. According to the diagram of critical velocities for erosion, transport, and deposition of sediments, the least flow velocity is required for fine and medium sand to start moving [21]. Sands with d ~ 0.1–0.3 in the reach from Muksuninskii Cape to Vasil'evskii Isl. are eroded at the velocity of 0.2–0.3 m/s and can participate in the formation of the third zone of higher turbidity in branches of bayhead, which forms downstream of the

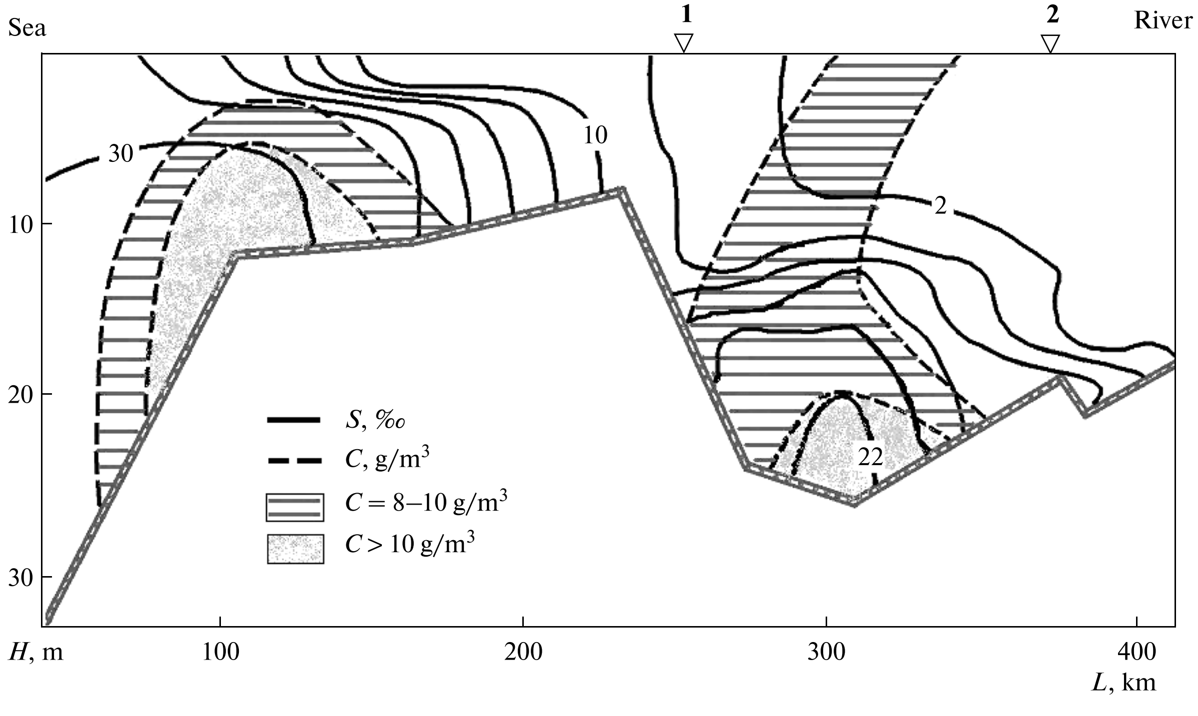

Fig. 5. Longitudinal profile of the bed in the reach between estuary mouth section and Baikalovo Settl., distribution of S, ‰, and turbidity C, g/m^3 [34, 35]; (1, 2) sections Sopochnaya Karga and DC, respectively.

boundary of maximal penetration of brackish waters into the estuary in the reach Karaul Settl.–Baikalovo Settl.

The distribution of water *C* along the estuary (Fig. 5) was derived from the results of averaging measurements made within several days; therefore, it does not reflect variations of *C* depending on tidal phase. The effect of tides on *R* can be illustrated by data in [12] on changes in *R* at gauges of the Bol'shoi and Kamennyi Yenisei before their confluence at $Q = 17000$ m^3/s. The amplitude of tides at the moment of measurements at Baikalovo gauge was 0.3 m. During the high tide phase, *Q* in those branches are 3530 and 930 m^3/s, and *R* are 140 and 18 kg/s, respectively; during the ebb tide, *Q* in the branches are 12540 and 3830 m^3/s, *R* are 12 and 2 kg/s, respectively. The sediment discharge in those gauges during high tide is far in excess of *R* at the ebb tide, a fact that indirectly corroborates the possible upstream transport of sediments in the bottom zone.

Thus, the opinion of the authors of [3] that "the processes of Yenisei delta formation are fully governed by river factors" is too categorical. In [3], during the analysis of the formation stages of the modern Yenisei delta, the authors mention the formation of a mouth bar at Muksuninskii Cape, which might have formed with the participation of inverse currents of brackish waters penetrating into the estuary.

CONCLUSIONS

The zoning of Yenisei mouth area showed that flows in delta branches participate in estuarine water circulation. In summer and autumn, water stratification in the estuary increases upstream from the mouth section, reaching its maximum at a distance of ~160 km from the mouth, after which it decreases at Sopochnaya Karga cape, where the current becomes almost completely mixed over the vertical; further upstream, flow stratification again increases and flow remains strongly stratified up to Baikalovo Settl. Analysis of changes in the vertical profiles of water salinity and turbidity along the estuary showed two zones of maximal turbidity to form in the estuary: one (at Sopochnaya Karga Cape) is due to the abrupt decrease of channel cross-section and depth; the other zone forms because of channel deepening and the closeness to the penetration boundary of brackish waters into the estuary. The presence of zones with mean diameter of sediment particles increasing downstream can be partially due to upstream transport of sediment by reverse brackish flow and its deposition at the moment of change of the currents.

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