ISSN 0001-4370, Oceanology, 2018, Vol. 58, No. 4, pp. 593–600. © Pleiades Publishing, Inc., 2018.
Original Russian Text © N.A. Rimskiy-Korsakov, V.N. Korotaev, V.V. Ivanov, A.A. Pronin, N.A. Demidenko, 2018, published in Okeanologiya, 2018, Vol. 58, No. 4, pp. 640–648.

MARINE GEOLOGY

Hydrological Regime and Lithodynamic Processes in the Mezen River Estuary

N. A. Rimskiy-Korsakov[a, *], V. N. Korotaev[b, **], V. V. Ivanov[b], A. A. Pronin[a], and N. A. Demidenko[c, *]**
[a]*Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, 117997 Russia*
[b]*Moscow State University, Moscow, 119991 Russia*
[c]*Zubov State Oceanography Institute, Moscow, 119034 Russia*
**e-mail: nrk@ocean.ru*
***e-mail: vlaskor@mail.ru*
****e-mail: nikola@mail.ru*
Received December 20, 2016

Abstract—In the Mezen River estuary, morpholithodynamic processes are regulated by tidal currents, river runoff, wind waves, and alongshore sediment flows. Due to the movement of a huge mass of sediments in the Mezen River estuary, intense deformations of silty sand banks occur, reforming the bottoms of channel grooves and displacing navigable waterways. On the whole, the Mezen River estuary is gradually being filled with river and marine sediments. Various sandy ridges form in the channel grooves of the estuary.

DOI: 10.1134/S0001437018040070

INTRODUCTION

A modern approach to categorizing estuarial sedimentation systems assumes their unification into two large groups: (1) wave-dominated estuaries and (2) tide-dominated estuaries [14]. Based on the natural conditions of Russia's coasts, it is possible to add a third dynamic-facies variety to these two groups: river-dominated estuaries. These should include, first, the long (hundreds of kilometers) and relatively narrow bays on the Siberian Arctic coast: the Ob, Taz, Yenisei, Khatanga, and Anabar, where owing to relatively small flood tides (less than 1 m), a runoff current regime prevails. In southern Russia, Taganrog Bay in the Sea of Azov is a typical river estuary that receives the waters of the Don. The sea's influence in such estuaries is limited by the penetration of maximum sediments and saline water. The south of the Russian Far East hosts the vast Amur estuary, in the lower reaches of the Amur River.

In typical estuaries under the strong action of reversing flood tide currents (the Onega, Mesen, Kuloy, Gizhigi, and Penzhina river estuaries), longitudinal variation in suspended and bed-load sediments signficantly differs from the terrigenous material budget in ingression bays with small flood tides. The main distinguishing feature of such estuaries is stratification of the water column into freshwater river and saline seawater layers of differing density, where advection and diffusion processes are significantly intensified. Estuaries with a distinctly manifested halocline are characterized by predominant runoff currents, and the effect of flood tides plays an insignificant role in water circulation. When the role of flood tides in estuarial water movement increases, the boundary between freshwater river water and saline seawater becomes less distinct, or it is not manifested at all [13, 21].

In 2005, 2007–2009, and 2015, the authors of the present paper had the opportunity to conduct hydrological and geophysical field research in the estuary and mouth of the Mezen River and obtain novel data on the water and sediment regime, bottom morphology, and composition of bottom sediments.

RESEARCH METHODS

To study the hydrological regime of the Mezen River estuary, we used GM-28 tide gages and two types of autonomous loggers: a Levelogger Solinist model 3001 LT F15/M5 and a Levelogger Edge model 3001, which recorded sea level, temperature, and salinity readings. The spatial positioning of instantaneous levels was carried out with a DGPS Trimble 5700 receiver (which was the base station at a reference point belonging the Semzha hydrometerological station) and portable JavadTriumph-VS and JavadTriumph-1 receivers.

The current and tidal flow rates in the Mezen estuary were measured with ISP-1 flowmeters and 1200 Rio Grande and River Ray acoustic Doppler current profilers (ADCP).

A YSI 6600 hydrological probe was used to measure water temperature and salinity at daily stations and in longitudinal transects along the estuaries. To determine the SPM concentration in different zones of the estuaries, water samples were taken from the surface horizon with a plastic container and from deep horizons with a 3 L Niskin bottle. The grain-size composition of SPM in seawater was determined with a Malvern Instruments MasterSizer M7.08 laser device at the Zubov State Oceanography Institute.

When studying the subaqueous relief and bottom sediments, the authors used sonar instruments developed at the Sonar Bottom Research Laboratory (SBRL) of the Shirshov Institute of Oceanology (IO RAS). Geodetic coupling of sonar information and the bottom sediment sampling was done with a Javad Sigma-G3T differential GPS receiver using GPS and GLONASS satellite constellations. Sonar instruments included an Imagenex YellowFin three-channel side-scan sonar (SSS) with operating frequencies of 260, 330, and 800 kHz; an AP-5-IORAN acoustic profiler with an operating frequency of 4.5 kHz; and a FortXXI Scat-50M hydrographic surveying echo sounder. The obtained information was collected and imaged in real time on a PC monitor. The operation of the acoustic profiler was controlled by the original EchoGraph software program developed by the SBRL. The original program WinRastr was used to preprocess the data into a form convenient for standard processing software.

SSS, mapping, and decoded seismic profile data were used to estimate the quantitative parameters of the bottom relief for subsequent mapping of the bottom morphology and artificial objects. This technology was developed and employed in channel operations by IO RAS and the Faculty of Geography of Moscow State University (MSU) [19, 20].

RESEARCH HISTORY OF THE MEZEN RIVER ESTUARY

The first studies on the hydrological regime of the Mezen River estuary were performed in 1914–1915 in the course of port surveys [2, 3]. In Soviet times, they were continued in 1928–1931 and 1934 by the Department of Survey for Northern Ports (Sevportiz). Drevstroi in 1929 and the Northern Hydrographical Expedition in 1930–1931 took part in engineering studies. As a result of these works, the first detailed map of the estuary was compiled and the first writings on its hydrology were published [18].

In conjunction with the plan to build a tidal power station (TPS) in 1958–1961, engineering surveys were carried out in the Mezen and Kuloy estuaries by the Leningrad branch of the Hydroenerproekt Institute and periodically by the Lenhydroproekt Institute in 1977, 1978, and 1988 [5].

In 1960 and 1965–1968, the Shirshov Institute of Oceanology of the USSR Academy of Sciences conducted research on the geological and geomorphological structure of the bottom and shores of Mezen Bay and the estuaries of the Mezen and Kuloy rivers, as well as the lithology of loose sediments at the site of the future Mezen TPS [10, 16].

In 1964–1968, the Northern Department for Hydrometeorology and Environmental Monitoring (NDHEM) continued to study the estuary region of the Mezen and Kuloy rivers [22]. In 1978, the NDHEM and Zubov State Oceanography Institute (GOIN) carried out a joint hydrological expedition in the estuaries of the Mezen and Kuloy rivers, as did GOIN and the Institute for Water Problems of the USSR Academy of Sciences in 1988–1989. GOIN employees conducted field observations in the winter period of 1990 [17].

Owing to renewed interest in the TPS in 2005, 2007, and 2009, employees of GOIN and MSU conducted summer engineering and hydrological surveys in the estuaries of Mezen Bay rivers—the Mezen, Nes, and Semzha—to assess possible ecological consequences [7]. In the winter period of 2005 and 2008, the state of fast ice, drift ice, and the physical characteristics of ice formations in the water area of Mezen Bay were studied [10]. During June and August 2015, employees of IO RAS, GOIN, and MSU conducted expeditionary research in the Mezen and Kuloy river estuaries to study the subaqueous relief and bottom sediments, parametrize individual elements of the hydrological regime, and perform long-term hydrological modeling of processes there.

HYDROLOGY OF THE ESTUARY

Mezen Bay and the Mezen River estuary lie in the eastern part of the White Sea. The marine boundary of the bay is the line connecting capes Voronov and Konushin. Within these limits, the water area of the bay occupies 6800 km^2. The bay is shallow and extends 92 km into the mainland. The shores of the bay are divided by deep, narrow river valleys. The most significant among them are the Mezen, Kuloy, Koida, Nes, Chizha, and Semzha rivers, which flow into the widening funnel-shaped near-mouth areas of the river valleys, i.e., estuaries.

The mouth region of the Mezen pertains to the estuary type. It has a complex structure that includes the river area subjected to fluctuations in the flood tide level, a tidal estuary that widens downstream, and a nearshore zone: the southeastern part of Mezen Bay (Fig. 1). The head of the Mezen River estuary is situated 90 km from the estuary–sea zone, near the inflow area of the Peza River, a large right tributary of the Mezen [13]. The Mezen's estuary–sea boundary is the imaginary line between Cape Maslyanyi and Cape Ryabinov. The head of the Mezen estuary is located 40 km from the estuary–sea boundary, near the town

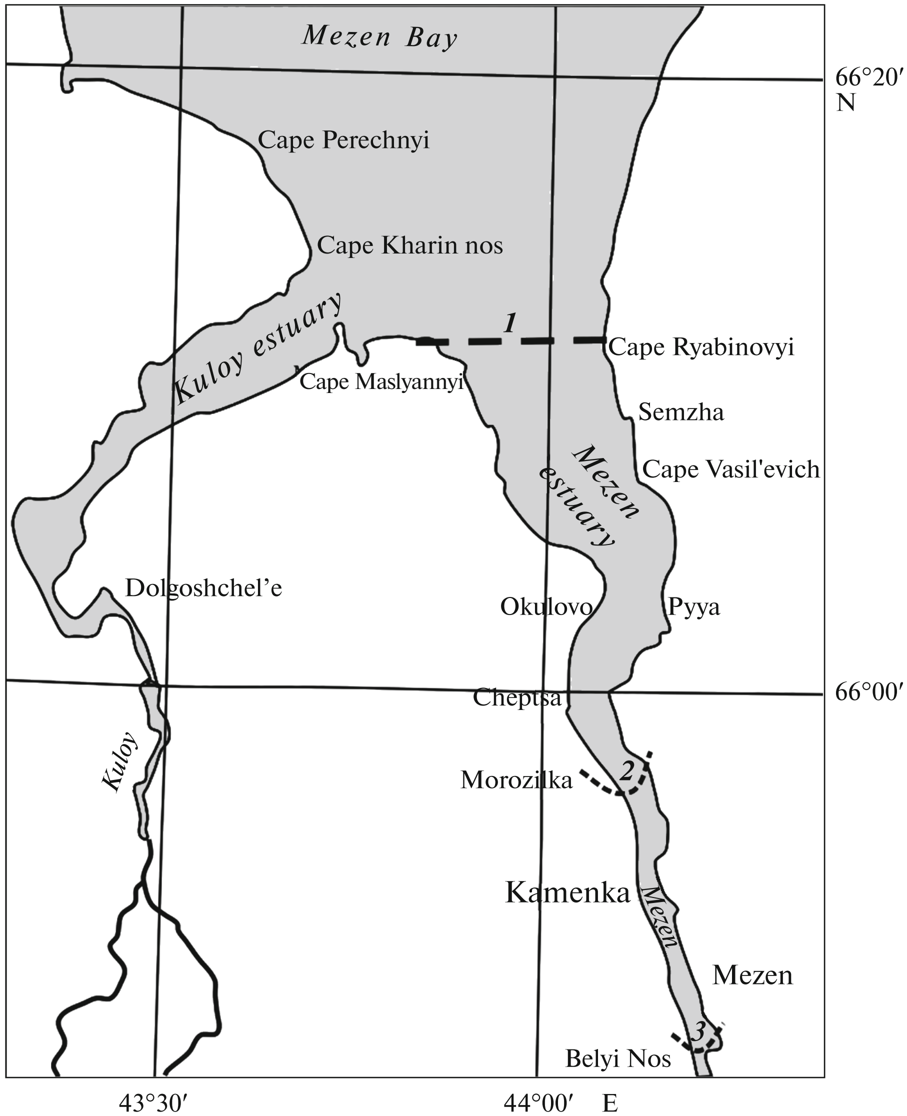

Fig. 1. Map of Mezen estuary region. (*1*) Mezen estuary–sea boundary; (*2*) boundary of seawater penetration into Mezen estuary; (*3*) head of Mezen estuary.

of Mezen. The nearshore of the estuary is bounded from the north by the imaginary line between Cape Abramovskii and the mouth of the Mgla River, coinciding with the 10 m isobath.

In terms of hydrological and geomorphological processes, the nearshore part of the estuary is semiclosed and shoaly [12]. The width of the nearshore of the estuary is 48 km, and the length from the estuary–sea boundary to the sea–nearshore boundary is around 30 km. The mean depth of the nearshore is 6–8 m. The surface area of the 40 km Mezen estuary during the flood tide is 162 km^2. The total surface area within the mouth area taking into account the estuary is 195 km ^{2}.

The width of the Mezen estuary at the estuary–sea boundary is 9.0 km; higher upstream, it gradually decreases: 16.5 km from the estuary–sea boundary (near the village of Okulovo) it is 4.5 km; near the settlement of Kamenka (36 km), it decreases to 1.8 km; and near the settlement of Belyi Nos (39 km), to 1.35 km. The head of the estuary is situated 40 km from the estuary–sea boundary near Cape Belyi Nos.

The walls of the Mezen River valley consist of relatively hard rocks (red and white marl, clayey shale) bearing traces of erosional impact. The river valley was downcut by 10–20 m into a littoral plain. The left bank of the Mezen consists of high bluffs with the exception of an area near the settlement of Morozilka and the village of Okulovo, where the bank at a distance of 10 km passes into the wetlands of the Bol'shie Cheptsy River valley. The right bank of the Mezen is low and

Table 1. Characteristics of flood tidal wave in Mezen estuary [22]

Location	Distance from estuary–sea boundary, km	Channel width, km	Magnitude of tide, m	
			syzygy	quadrature
Mezen Bay				
Cape Lukhanov	–16.0	31.0	7.28	4.70
Cape Elovyi	–7.5	19.0	7.65	4.78
Mezen estuary				
Cape Masyanyi	0.0	9.0	(7.8)	(4.9)
Village of Semzha	6.0	7.5	7.82	5.13
Cape Vasil'evich	9.0	6.0	7.46	5.10
VIllage of Okulovo	16.5	4.5	5.84	4.11
Settlement of Morozilka	27.0	1.8	4.44	3.09
Settlement of Kamenka	36.0	1.8	3.74	2.52
Cape Belyi Nos	39.0	1.3	3.28	2.06
Estuary area				
Settlement of Zaton	63.0	1.0	0.72	0.02

Parentheses contain approximate values.

waterlogged, and only near capes Simonov and Basil'evich does its height increase to 30 m.

The estuarial area of the Mezen River is used for maritime and river navigation, as well as local fishery. The mouth of the river is near the town of Mezen (the local center of Arkhangel oblast) and the settlement of Kamenka, which hosts the Mezen seaport and lumber factory. Maritime navigation goes no farther than Kamenka (36 km from the estuary–sea boundary). Higher than Kamenka, the Mezen is only navigable by river craft.

The dry land adjacent to Mezen Bay consists of level wetlands with a local absolute elevation of 0–85 m. It falls away toward the sea in the form of an abraded scarp with a height of 10–30 m. The shores consist mainly of loose glacial-marine deposits. The gradual contours of the coastline are occasionally broken by small capes. Much of the territory is waterlogged. Glacial, karst, and kettle lakes abound.

HYDROLOGICAL REGIME OF THE MEZEN RIVER AND ESTUARY

In the observation period from 1921 through 2015, **the mean annual water discharge rate** at the head of the estuarial region of the Mezen River was 800 m^3/s, and annual runoff was 27.4 km^3/yr. The main phase of the water regime is the spring–summer flood, which begins at the end of April–beginning of May. The maximum water discharge rates are usually observed in May and reach 10000 m^3/s. The summer–fall runoff low is intermittent, broken by rainfall floods with increased runoff in the fall period.

At the head of the Mezen River estuary, the mean water turbidity is 30 g/m^3; during the flood season, it increases up to 100 g/m^3. **The mean annual sediment discharge** is around 20 kg/s; for SPM, it is 0.8 mln t/yr.

The main factors determining the **water level regime** of the Mezen River estuary are tidal fluctuations and river runoff. Closer to the estuary, the regular semidiurnal flood tide becomes irregular and shallow: the duration of rise decreases, and the duration of fall increases. The spring flood tide in the area of the estuary–sea boundary near the village of Semzha reaches 8.5 and 4.8 m at quadrature. The mean water level recorded by the Semzha hydrometeorological station is 350 cm above local zero, or 26 cm above zero on a Kronstadt tide gage. The interannual spread of water level fluctuations at the Semzha hydrometeorological station is 1003 cm. Beginning from the village of Semzha upstream along the Mezen estuary, the flood tides rapidly decrease in magnitude. At the head of the estuary (Cape Belyi Nos), the flood tide decreases by 60% (Table 1).

The water dynamics in the Mezen estuary is determined mainly by the flood tides. Increased flow rates lead to tidal water flow rates multiply exceeding the river discharge rates during the flood season. This in turn facilitates flood-tidal erosion and widens channels in the estuary.

Flood tide currents, which in Mezen Bay have an elliptical character, transform from rotary to reversing on the Cape Krasnyi traverse 40 km from the Mezen estuary–sea boundary [4]. The maximum current speeds of flood (reversing) tides exceed the maximum speeds of direct (ebb) tides. This is because the duration of fall exceeds the duration of rise, and large reverse water surface slopes form a short time after the current changes from direct to reversing. There is an increase in the influence of shallow water on the flood-tidal wave dynamics. At all White Sea bayheads, the flood-tidal wave amplitude increases significantly in accordance with Green's law (the flood-tidal energy is concentrated as a bay's cross section narrows).

At the village of Semzha, the flood tide reaches the maximum value within the estuary. This is manifested as asymmetry in the tidal currents. The duration of the incoming tidal current is around 5 h; of the ebb tideal current, 7.5 h. During spring tides, the highest incoming tidal current speeds in this area are seen 3 h after low water (LW) and within 2–3 h before high water (HW) and reach 1.6–1.8 m/s; the highest outgoing tidal current speeds are observed 3 h after HW and reach 1.2 m/s. During neap tides, the highest incoming tidal current speeds reach 1.2–1.4 m/s, and the highest outgoing tidal current speeds reach 1.2 m/s. When the currents change to HW and LW, the speeds drop almost to zero. However, currents change almost instantaneously from direct to reversing and vice versa. In the incoming tidal phase, the change in currents begins near the shore and bottom, then it spreads to the entire cross section of the channel. In the outgoing tidal phase, the change in currents from reversing to direct (seaward) occurs first in the main part of the flow and then spreads quite rapidly to the entire flow.

The value of water mass movement during the tidal cycle up- and downstream the Mezen estuary is 10 km, on average. In winter, the range of tidal propagation and the current speed decrease.

In other spots of the estuary, the tidal current speeds may be appreciably larger than in the lower estuary. In the area of Cape Tolstik and the mouth of the Pyya River, the current speed during the flood tide reaches the values largest for the Mezen estuary: up to 3.0 m/s. Toward the head of the estuary, the incoming tidal current speeds decrease. Near the village of Okulovo, the incoming tidal current speeds reach 1.8 m/s; the outgoing tidal current speeds reach 1.6 m/s; near the settlement of Kamenka, the incoming tidal current speeds reach 1.6 m/s.

In Mezen Bay, at the imaginary line between capes Abramovskii and Mikhailovskii, the total currents during the flood tide have directions of 130°–150°; during the ebb tide, 330°–350°. During the flood tide, the total currents at the line between the Vysypnoy and Mgla beacons have directions of 120°–200°; for the ebb tide, the direction varies from 300° to 0°. At syzygy, the maximum current speeds during the flood tide are 2.0 m/s; for the ebb tide, 1.9 m/s. At quadrature, during the flood tide, the maximum current speeds are 1.3 m/s; during the ebb tide, 1.2 m/s. For the intermittent period in the incoming tidal phase, the maximum current speeds are 1.7 m/s; for the outgoing tidal phase, 1.4 m/s.

On the line between capes Perechnyi and Elovyi, the total current speeds at syzygy during the flood tide reach 1.9 m/s; for the ebb tide, 1.7 m/s. On the line between the Vysypnoi and Mgla beacons, at syzygy, during the flood and ebb tides, the maximum current speeds reach 1.5 m/s; at quadrature, during the flood tide, the maximum current speed is 1.2 m/s; for the ebb tide, 0.9 m/s.

The mean power of an incoming tidal wave at the mouth of the Mezen River estuary is around 2 mln kW; the incoming tidal discharge rate at the estuary–sea boundary reaches 100000 m^3/s [15].

The currents transport sediments of different size and create a high-turbidity zone in the estuary, a "traffic jam of murk" with a maximum concentration of tide-disturbed sediments up to 10–13 km/m^3, the core of which is located 15–20 km from the estuary–sea boundary. Thus, e.g., near the village of Pyya, the turbidity in the near-bottom horizon fluctuates from 0.5 to 8.5 kg/m^3 (mean of 3.5 km/m^3), while near the village of Semzha, it is from 0.35 to 13. kg/m^3 [6, 9].

In the Mezen estuary, the river–seawater mixing zone stretches nearly 30 km. **Salinity** in the Mezen estuary varies in a wide range from the summer maximum (21–22‰) to the spring minimum (1–2‰). The maximum water salinity values (26‰) are observed during spring flood tides and storm surges in the summer low-water season. The mean value for longitudinal salinity gradients is 1.5–2.0‰/km, reaching values of 3–4‰ in some areas. The vertical salinity gradient does not exceed 0.1–0.4‰/m.

MORPHOLITHODYNAMICS OF THE ESTUARY

The water area of the Mezen estuary from the head to the estuary–sea boundary is filled with nearshore sand banks and semisubmerged midchannel bars with depths from 0.5 to 3 m. Overdeepened areas of the bottom of the estuary lie between the sand banks and midchannel bars in the form of winding channel grooves with depths from 3 to 7 m (Fig. 2).

The nearshore sand banks, whose widths fluctuate from 100 to 700 m, are sandy-silty emergent forms beneath the bluffs on both sides of the estuary. The upper nearshore part of a sand bank consists of sand mixed with boulders. Whereas the upper part of a sand bank is weakly subjected to erosion even during spring flood tides and in the storm surge period, it is reinforced by moderately halophytic vegetation, forming tidally submerged plains (laidas) or marshes. The middle part of a sand bank is taken up by round boulders and gravel, forming small ridges. The seaward edge of a sand bank is made up of silt deposits up to 1 m thick.

The middle part of the water area of the estuary from the settlement of Morozilka to the settlement of Semzha is taken up by sandy ridges in the form of semisubmerged fine-sand midchannel bars, the dimensions of which gradually increase downstream from 8 to 24 km^2. The overdeepened channel grooves along which tidal waters move are lined with medium- and fine-grained sands mixed with gravel and pebble.

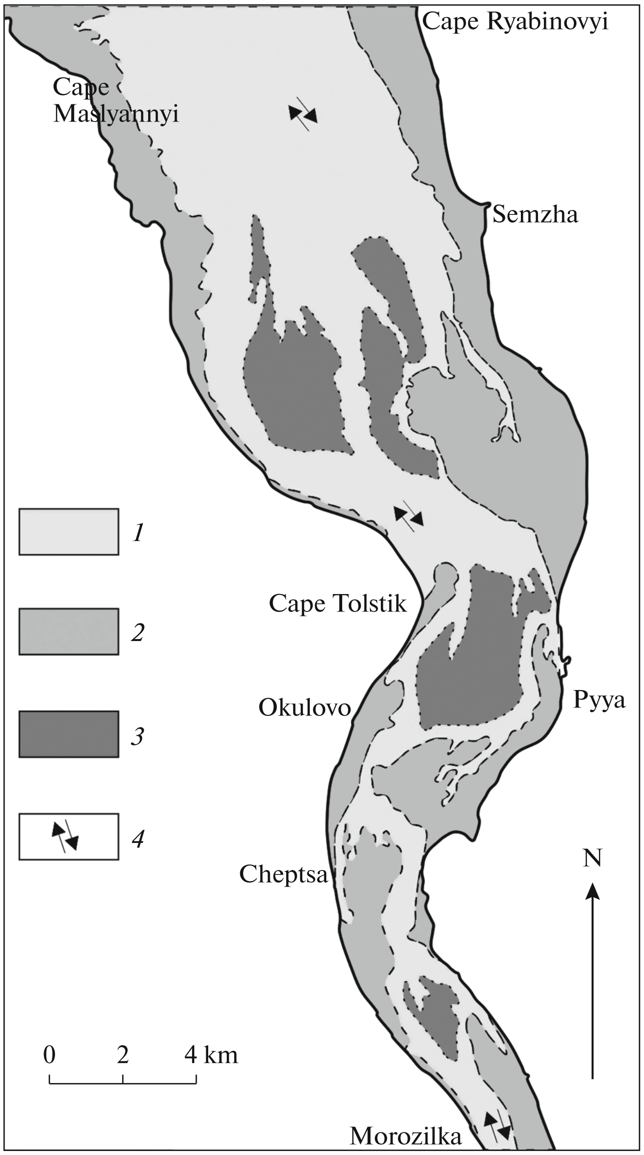

Fig. 2. Diagram of nearshore sand banks and midchannel bars in Mezen estuary. (*1*) Water area of estuary; (*2*) nearshore sand banks (exposed); (*3*) midchannel bars; (*4*) current directions.

Based on the results of hydrographical (bottom echo-sounding) and geophysical (hydroacoustic bottom mapping) field studies in the Mezen estuary, a complex hierarchy of sandy ridges in the subaqueous relief of channel grooves has been established (Fig. 3). The largest elements of this hierarchy are so-called *sand waves*, the lengths and heights of which fluctuate from 13 to 20 km and from 5 to 7 m, respectively (Table 2). The smallest accumulative bottom formations are *ripples* less than 10 m long and 0.1 m high.

Intermediate elements of the hierarchical system among subaqueous accumulative forms in the Mezen estuary are *dunes* and *bars* (after N.I. Alekseevskii's classification [Cyrillic (transliteration)]: В (V), Г (G), Д (D), and А (A), Б (B). The first form ridges from 360 to 15 m long and 1 to 0.15 m high; the second form large ridges from 3880 to 800 m long and 4.9 to 1.1 m high (Fig. 4).

Analysis of statistical data has shown certain differences in the parameters of the hierarchical system of sandy ridges within the Mezen estuary. In particular, V, G, and D type ridges [1] have different morphometric parameters (length and height) near the head of the estuary and the estuary–sea boundary, which are clearly related to variation in the tidal current characteristics. The smallest sandy ridges of the bottom relief (ripples) in different areas of the estuary have close morphometric indices (Table 2).

At the head of the estuary, river sediments have formed an entire system of emergent islands along the right (eastern) wall of the Mezen River valley. The islands of Seredovaya Koshka, Zarech'e, and Baluikha make up a natural stage in the formation of supraqueous tidal river deltas. The chain of islands near the right bank below the town of Mezen continues with the islands of Vanyushina Koshka, Maksimova Koshka, Shestakova Koshka, Ostrovok, and Mishina Koshka.

The ebb tide carries away unaccumulated bottom sediments from the estuary and deposits them in the southern part of the Voronka inlet of the White Sea at the mouth of Mezen Bay, where as a result, submarine ridges form (the Severnye Koshki): Bol'shara Orlovskaya Koshka, Bol'shaya Srednyaya Koshka, Konyshinskaya, and Kiiskie Meli [10]. Similar ridges, so-called giant sand waves, are typical tidal accumulations of sandy material under conditions of strong incoming tidal currents on the shelves of seas and are encountered in various estuaries. Some of them emerge in low water during spring tides, but most remain submerged.

CONCLUSIONS

The morpholithodynamic processes in the Mezen estuary are regulated by tidal currents, river runoff and sediments, wind waves, and alongshore sediment flows.

Powerful tidal currents predetermine the high dynamism of the estuary's bottom relief. According to data from an analysis of navigational charts, the main channel for the movement of tidal waters in the area of the Semzha and Pyya rivers was displaced in the period of 1893–1960 from the eastern to the western side of the estuary.

According to abrasion intensity estimates for the shores of the estuary (e.g., within 5 years, the shore receded by 15 m in the area from the Semzha River mouth to Cape Ryabinov), the amount of detritus delivered to the nearshore from abrasion of Mezen Bay's coasts reaches 30 mln t/yr [16].

Owing to the movement of a large mass of sediments in the Mezen estuary, intense deformations of

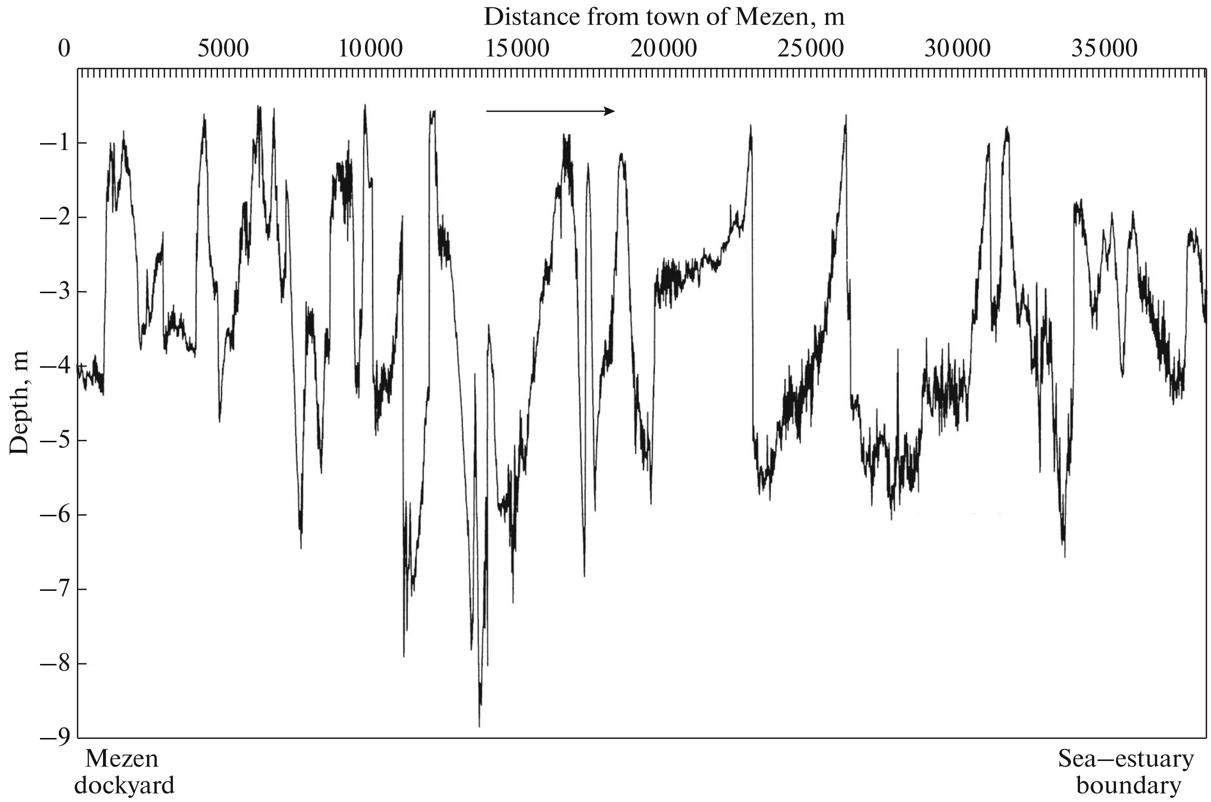

Fig. 3. Longitudinal echo-sounding profile of bottom of Mezen estuary from head to estuary–sea boundary.

silty-sandy ridges occur, reforming the bottom and abruptly displacing navigable waterways. As a consequence, the town of Mezen, which in the 16th century was located on the shore of the estuary, is now separated from the river by a 2.5-km-wide delta floodplain. On the whole, the Mezen River estuary is gradually filling with river and marine sediments. Since the first instrumental research of the bay in 1914–1915, the depths near the estuary–sea boundary have decreased by 2–3 m. These same trends are characteristic of the head of the estuary near the town of Mezen.

In the nearshore zone, incoming tidal currents and wind waves of various direction aid in creating complex accumulative bottom formations. The most widespread are so-called sand waves or giant ripples (koshki): a series of ridges up to 0.5 m in height that form on the ridged bottom (with slopes of less than 0.005) at current speeds of 0.3–0.8 m/s.

From the coastal areas of Mezen Bay subjected to abrasion and owing to suspended sediment material from the Mezen and Kuloy rivers, the ebb tide transports fine-grained sand and silt to the north, where

Table 2. Characteristics of ridge parameters (l, length; h, height) in Mezen estuary

Areas	Sand waves		А bars		Б (B) bars		В (V) dunes		Г (G) dunes		Д (D) dunes		Ripples	
	l	h	l	h	l	h	l	h	l	h	l	h	l	h
Estuary (town of Mezen)	>13000	5–6	2000–3800	3.5–4.9	800–1350	1.6–3.0	240–360	0.8–1.0	40–50	0.3–0.45	20–30	0.15–0.2	<10	<0.1
Estuary–sea boundary	>20000	5–7	1800–2800	3.5–4.4	820–900	1.1–2.4	80–110	0.2–0.5	40–60	0.15–0.3	15–25	0.1–0.15	<10	<0.1

Hierarchical ridge structure А (A), Б (B), В (V), Г (G), Д (D) after Alekseevskii [1].

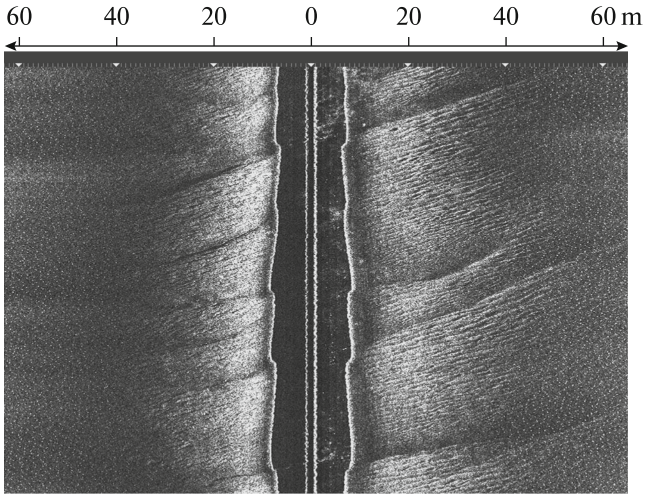

Fig. 4. Sonar image of sand dunes in channel groove of Mezen estuary.

sand accumulates and sand waves form when current speeds decrease. Fine-grained SPM is transported out of the nearshore zone farther into the White Sea.

ACKNOWLEDGMENTS

The study was supported by the Russian Foundation for Basic Research (project nos. 13-05041001, 16-05-01018) and the Russian Science Foundation (project nos. 14-17-00155 and 14-37-00038).

REFERENCES

1. N. I. Alekseevskii, *Development and Transfer of the River Alluvia* (Moscow State Univ., Moscow, 1998) [in Russian].
2. A. M. Vikhman, "Research works in the ports of White Sea in 1910–1915," Tr. Otd. Torgovykh Portov, No. 54, 34–41 (1917).
3. A. M. Vikhman, "The speed of flow and the number of alluvium in the mouth of the Mezen River," Izv. Tsentr. Gidrometeorol. Byuro, No. 5, 11–17 (1925).
4. *Hydrometeorology and Hydrochemistry of the Seas of Soviet Union*, Vol. 2: *The White Sea*, No. 1: *Hydrometeorological Conditions* (Gidrometeoizdat, Leningrad, 1991) [in Russian].
5. V. M. Gorelkov, L. N. Grigor'eva, and M. L. Monosov, "Transformation of semi-diurnal tide in the northern part of the White Sea due to construction of Mezenskaya Tidal Power Plant," Tr. Lengidroproekta, No. 77, 74–80 (1981).
6. N. A. Demidenko, "Spatio-temporal changes of concentration of suspended matter in tidal river estuaries in northern Russia," *Proceedings of IV Conference "Dynamics and Thermal Conditions of Rivers, Water Reservoirs, and Coastal Zone of the Seas"* (Water Problems Institute, Russian Academy of Sciences, Moscow, 1994), Vol. 2, pp. 93–94.
7. N. A. Demidenko, I. V. Zemlyanov, O. V. Gorelits, and V. N. Mikhailov, "Hydrological and morphological processes in estuarine area of Mezen River to design of Mezenskaya Tidal Power Plant," Tr. Gos. Okeanogr. Inst., No. 211, 273–288 (2008).
8. N. A. Demidenko, "Maximum turbidity of water in the strong tidal estuaries of the Mezen and Kuloi rivers," *Proceedings of XVIII International Scientific Conference (School) on Marine Geology "Geology of the Seas and Oceans"* (GEOS, Moscow, 2009), Vol. 4, pp. 65–69.
9. N. A. Demidenko, "Hydrological regime of the Mezenskii Bay and estuaries of Mezen and Kuloi rivers," in *The White Sea System*, Vol. 2: *Water Column and Interacting Atmosphere, Cryosphere, River Run-Off, and Biosphere* (Nauchnyi Mir, Moscow, 2012), pp. 411–432.
10. *Sailing Directions in the White Sea* (General Directorate of Navigation and Oceanography, Ministry of Defense, St. Petersburg, 1996) [in Russian].
11. V. S. Medvedev, "Dynamics of the coastal zone of Mezenskii Bay of the White Sea related to design of tidal power plants," in *Geomorphology and Lithology of the Coastal Zone* (Nauka, Moscow, 1971), pp. 23–29.
12. V. N. Mikhailov, *Estuaries of the Russian Rivers and Adjacent Countries: Past, Present, and Future* (GEOS, Moscow, 1997) [in Russian].
13. V. N. Mikhailov and E. S. Povalishnikova, "Estuary area of a river as a zone of dynamic interaction and mixing of river and marine waters," Vestn. Mosk. Univ., Ser. 5: Geogr., No. 5, 29–37 (1992).
14. V. N. Mikhailov, S. L. Gorin, and M. V. Mikhailova, "New approach to the definition of estuaries and to their typology," Vestn. Mosk. Univ., Ser. 5: Geogr., No. 5, 3–11 (2009).
15. D. V. Mishin, "Variability of hydrological characteristics in the estuary of Mezen River during tidal cycle," *Proceedings of VII Conference "Dynamics and Thermal Conditions of Rivers, Water Reservoirs, and Coastal Zone of the Seas"* (Peoples' Friendship University of Russia, Moscow, 2009), pp. 462–470.
16. E. N. Nevesskii, V. S. Medvedev, and V. V. Kalinenko, *Sedimentogenesis and History in Holocene in the White Sea* (Nauka, Moscow, 1977) [in Russian].
17. V. F. Polonskii, Yu. V. Lupachev, and N. A. Skriptunova, *Hydrological and Morphological Processes in the River Estuaries and Their Calculation* (Gidrometeoizdat, St. Petersburg, 1992) [in Russian].
18. I. D. Protopopov, "The hydrological regime of the Mezen River," in *Study of the Seas of Soviet Union* (State Hydrometeorological Inst., Leningrad, 1932), No. 16, pp. 87–102.
19. N. A. Rimskiy-Korsakov, "Investigation of the bottom of reservoirs using sonar equipment," Oktopus Pro, No. 5, 56–58 (2002).
20. N. A. Rimskii-Korsakov, A. A. Pronin, and U. S. Dolotov, "Technology for bottom relief and sedimentation surveys of White-Sea river estuaries," Oceanology (Engl. Transl.) **49**, 432–437 (2009).
21. G. A. Saf'yanov, *Estuaries* (Mysl', Moscow, 1987) [in Russian].
22. V. A. Sedelkov, "The levels and tides in the estuarine area of Mezen River," Sb. Tr. Arkhangel'sk. Gos. Meteorol. Obs., No. 7, 72–81 (1970).
23. *The White Sea System*, Vol. 2: *Water Column and Interacting Atmosphere, Cryosphere, River Run-Off, and Biosphere* (Nauchnyi Mir, Moscow, 2012) [in Russian].

Translated by A. Carpenter