DOI: 10.22449/2413-5577-2022-4-52-68

Hydrolithodynamic Conditions of Sediment Movement through the Strait of Baltiysk (Vistula Lagoon, Baltic Sea)

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Abstract
In the area of the strait connecting the Vistula Lagoon with the Baltic Sea, the work was carried out to refine the bottom topography, collect bottom sediments, measure currents in different seasons, and install a set of sediment traps at 4 levels in the 2-meter bottom layer. The sediment accumulation zones were identified on the basis of the bathymetric data according to geomorphological features. On the basis of *in situ* data, we studied the hydrolithodynamic conditions of suspended sediment movement through the strait and the general nature of sediment exchange. The suspended material moves through the strait both during inflows and outflows, while silt and fine sand are mainly transported from the lagoon into the sea, while fine, medium and coarse sands, on the contrary, are brought into the lagoon and feed the surge delta (a shallow area at the lagoonic end of the strait). Surge delta sediments mainly consist of fine and medium sand. It was assumed that the flow of sediments of sandy grain sizes does not reach the surge delta (the final deposition zone) in full, the part of the volume entering the strait is removed during regular maintaining dredging in the strait. Consequently, the surge delta develops more slowly than it could do naturally.

Keywords: strait, estuary, surge delta, lagoons, bottom sediments, suspended sediments, currents, sampling, field measurements

Acknowledgements: the authors are grateful to colleagues V.T. Paka, A.O. Korzh, A.A. Kondrashov for instrumentation support of current measurements, to A.N. Babakov for advice and partial preparation of sediment collection instruments, to V.S. Pinchuk and volunteer colleagues for participation in the expedition works. The fieldwork was carried out under cooperation agreement no. 4/2019 (1358) as of 3.07.2019 between Shirshov Institute of Oceanology RAS (Atlantic Branch) and Immanuel Kant Baltic Federal University and funded under RFBR project 19-35-90069 support, the interpretation of results is funded under state assignment of IO RAS (topic no. FMWE-2021-0016).

For citation: Zakirov, R.B., Chubarenko, B.V. and Chechko, V.A., 2022. Hydrolithodynamic Conditions of Sediment Movement through the Strait of Baltiysk (Vistula Lagoon, Baltic Sea). *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 52–68. doi:10.22449/2413-5577-2022-4-52-68

Гидролитодинамические условия движения наносов через Балтийский пролив (Калининградский залив, Балтийское море)

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Аннотация
В районе пролива, связывающего Калининградский залив с Балтийским морем, проведены работы по уточнению рельефа дна, отбору донных отложений, измерению течений в разные сезоны и установке набора наносоуловителей на четырех горизонтах в придонном 2-метровом слое. По геоморфологическим признакам выделены зоны осадконакопления. На основе натурных данных изучены гидролитодинамические условия движения взвешенных наносов и общий характер седиментообмена залива с морем. Движение взвешенного материала через пролив осуществляется как при затоках, так и при оттоках, при этом илистая и мелкая песчаная взвесь преимущественно выносятся из залива в море, а мелкая, средняя и крупная песчаные фракции, наоборот, заносятся в залив и подпитывают нагонную дельту (мель со стороны залива). Отложения нагонной дельты состоят в основном из мелко- и среднезернистого песка. Предполагается, что поток песчаных наносов достигает нагонной дельты (как конечной зоны депонирования) не в полном объеме, часть объема извлекается в процессе регулярного дноуглубления в проливе. В результате этого нагонная дельта развивается медленнее, чем могла бы в естественных условиях.

Ключевые слова: пролив, эстуарий, нагонная дельта, лагуны, донные осадки, взвесь, течения, натурные измерения

Благодарности: авторы благодарны коллегам В. Т. Паке, А. О. Коржу, А. А. Кондрашову за аппаратурное обеспечение измерений течений, А. Н. Бабакову за советы и подготовку оснащения наносонакопителей, В. С. Пинчуку и коллегам-волонтерам за участие в экспедиционных работах. Полевые работы выполнены в рамках договора о сотрудничестве Института океанологии им. П. П. Ширшова РАН (Атлантическое отделение) с БФУ им. И. Канта от 3.07.2019 №4/2019 (1358) за счет поддержки проекта РФФИ 19-35-90069, интерпретация – за счет госзадания ИО РАН (тема № FMWE-2021-0016).

Для цитирования: *Закиров Р. Б., Чубаренко Б. В., Чечко В. А.* Гидролитодинамические условия движения наносов через Балтийский пролив (Калининградский залив, Балтийское море) // Экологическая безопасность прибрежной и шельфовой зон моря. 2022. № 4. С. 52–68. EDN ZKQZYX. doi:10.22449/2413-5577-2022-4-52-68

1. Introduction

The Kaliningrad Bay/Vistula Lagoon (Fig. 1) is the second largest transboundary lagoon-type water body [1] on the coast of the Baltic Sea. Although the Russian part of the water area (56.2 %) is called the Kaliningrad Bay on official maps, and the Polish part is called the Vistula Lagoon [2], in the article we shall use the name Vistula Lagoon in accordance with [3]. The lagoon is separated from the sea by a sandy Vistula Spit [2] and is freely connected to the sea by a natural channel, which has no official name, but in the scientific literature, starting from the classic publication [3], it is listed as the Strait of Baltiysk [1)] (hereinafter referred to as the strait). Being the core of the natural and technical system [4] of the inlet section of the Kaliningrad Seaway Canal [2)], the strait is an important link in the system for ensuring the transport accessibility of Port of Kaliningrad. From autumn 2022, it has been no longer the only connection between the lagoon and the sea – a new artificially dug shipping canal has been opened in the southern part of the spit [3)], equipped with a lock that blocks free water exchange between the lagoon and the sea. The water area of the lagoon serves as a receiving reservoir for the rivers Pregolya, Paslenka, Prokhladnaya, Elblag, Bauda, Mamonovka-Bonuvka, Nelma, Nogat, etc., it receives both sea (17 km^3/year) and river (3.5 km^3/year) waters, and together with them terrigenous and biogenic material [3, 5, 6].

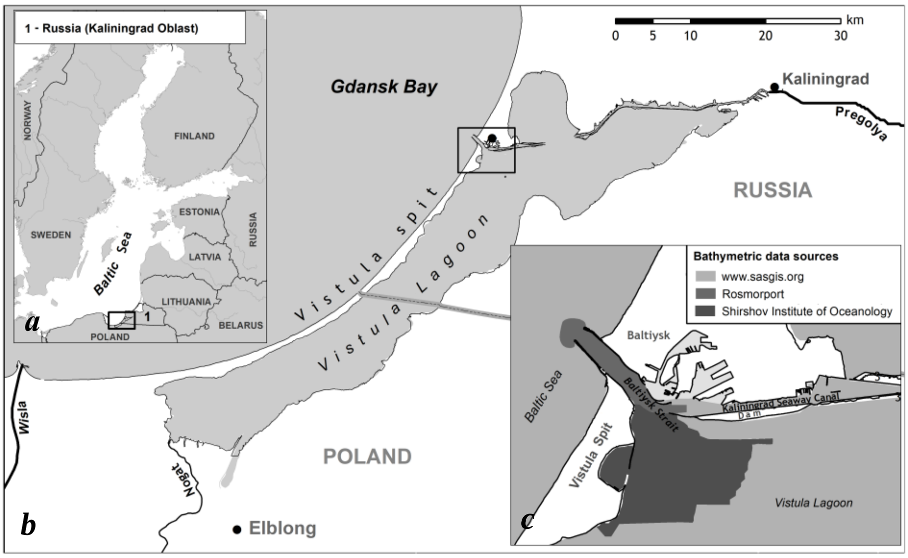
After almost complete regulation of the Nogat River flow in 1916, the flow of river waters and sediments into the lagoon water area sharply decreased and the role of water exchange through the Strait of Baltiysk increased [3]. The sedimentary balance of the lagoon water area was disturbed and, according to some assumptions, has not yet reached equilibrium [6]. According to the estimates [5, 7, 8], 76,500 tons of sedimentary material (60 % – biogenic suspended matter) are brought annually through the Strait of Baltiysk, and 348,400 tons per year are taken out of the lagoon into the sea (70 % – biogenic suspended matter). These estimates are based on short-term hydrological measurements of flows in the Strait of Baltiysk obtained during field work in 1951–1965 [3], and the results of numerical simulation [6, 8–10].

Based on the results of the bathymetric data analysis, we previously performed a morphometric description of the sand bank at the lagoon-ward end of the strait [11] and the erosional depression between the entrance pair breakwater piers of the seaward end of the strait [12], and based on the results of hydrological measurements, a relationship was revealed between the dynamics of the sea level and water exchange between the lagoon and the sea [13]. It was established [12] that the volume of erosion depression below the 12 m isobath is 1.13 mln m^3. In 2008–2016 the depression increased its size at a rate of 2450 m^3/year. The sand bank at the entrance to the Vistula Lagoon [11] has an annular shape with flush channels cutting through it; the volume of the sand bank above the 2.5 m isobath is estimated at 6.5 mln m^3, the deformation (during the period 2012–2019) was noted over its entire surface. The results obtained earlier testify to active hydrolithodynamic processes at the inlet and outlet of the strait.

[1)] The name "Baltic Strait" is absent in the Registry of Geographical Names of the Kaliningrad Oblast. In English-language literature (see Szydłowski, M., Artichowicz, W. and Zima, P., 2021. Analysis of the Water Level Variation in the Polish Part of the Vistula Lagoon (Baltic Sea) and Estimation of Water Inflow and Outflow Transport through the Strait of Baltiysk in the Years 2008–2017. *Water*, 13(10), 1328. doi:10.3390/w13101328), the name "Strait of Baltiysk" can be found (due to location near the city of Baltiysk).

[2)] The Kaliningrad Seaway Canal is stretched along the north coast of Vistula Lagoon from the strait to the mouth of the Pregolya River and is a navigable waterway connecting the port of Kaliningrad with the Baltic Sea.

[3)] The canal on the Polish part of the Vistula Spit was formally opened for navigation on 17 September 2022.



F i g . 1 . Study area: Baltic Sea (*a*); Vistula Lagoon in the South-Eastern Baltic (*b*); scheme of covering the study area with bathymetric data (*c*)

The flows over the sand bank [13] are subject to the regime features of the water exchange between the lagoon and the sea, they are bidirectionally oriented (toward the inflow of sea water and the outflow of water from the lagoon) and characterized by a frequent change of sign. A linear relationship was revealed between the value of the cumulative water exchange between the lagoon and the sea, as well as sea level fluctuations (regression coefficient r = 0.84…0.98).

At present, sediment flows through the strait have not been sufficiently studied; the field measurement data of 1951–1965 [3], on which modern estimates of suspended matter transport are based [6, 8], are already technically outdated and require clarification. The problem of balance in sediment exchange must be solved on the basis of data accumulation from the direct measurements of the suspended material flows.

The purpose of the work is to identify zones of sedimentation based on geomorphological features and experimentally, based on *in situ* data, to study the hydrolithodynamic conditions for the movement of suspended sediments in the area of the strait, which provides a free connection between the Vistula Lagoon and the Baltic Sea.

2. Research methodology

The paper implements a methodology for morphodynamic studies based on field measurements, sampling, processing and analysis of geological and geomorphological information.

The **digital topographic model** is based on bathymetric data from various sources: the single-beam echosounder measurements at the entrance to the Vistula Lagoon for 2012, the multibeam measurements at the offshore section of the Kaliningrad

Seaway Canal for 2011. The bathymetric data for the rest of the Vistula Lagoon and Gdansk Bay of the Baltic Sea were digitized using the library of SAS. Planet open geoinformation system (available at: www.sasgis.org) (Fig. 1, *c*). The processing and analysis of bathymetric data were performed using Esri ArcGIS 10.0 GIS software packages. A scheme of the bottom relief of the Strait of Baltiysk was prepared using standard surface mapping methods. Then, the sedimentation zones were identified based on morphological features, similarly to the sedimentation environment of the wave estuary [14–17].

The **sampling of bottom sediments** (layer 0.1–0.15 m) was carried out at three points (*B1*, *B2*, *B3* in Fig. 2) using a Van Veen single-rope clamshell bucket. The **sampling of suspended sediments** was carried out in accordance with methodological developments [18, 19]: a rigid pyramidal frame was installed at the bottom of the lagoon, on which cassettes with sediment traps of horizontal and vertical types were fixed at levels of 40, 100, 150, 200 cm from the bottom and 40, 100, 150, 200 cm from the bottom, respectively. The suspended sediments were collected at two points in the period from 28.06.2020 to 02.08.2020: at point *2* for 35 days, at point *7* for 18 days. At point *2*, only horizontal-type sediment traps were installed; at point *7*, both types of sediment traps were installed. Both horizontal- and vertical-type traps accumulate material regardless of the flow direction – the horizontal-type traps have side openings along the entire perimeter, the top end of the vertical-type traps is completely open.

The **granular composition** of the selected suspended matter and bottom material was determined by the mass content of particles of various sizes, expressed as a percentage relative to the weight of the dry sediment sample taken for analysis. The granular analysis was performed by sieve (fractions greater than 0.04 mm) and water-mechanical (fractions less than 0.04 mm) methods [20] by sifting a sandy sediment

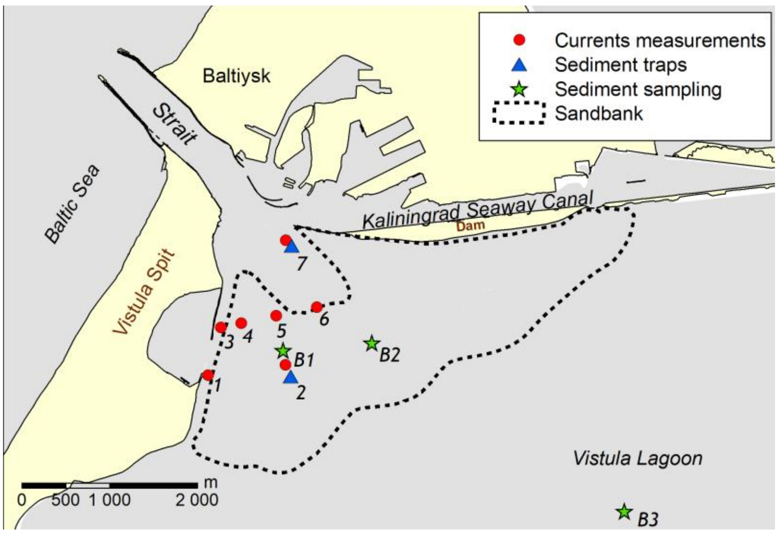


Fig. 2. Measurement and sampling map

sample through a set of sieves of an AS 200 analytical sieving machine. Based on the granular analysis results in accordance with the Wentworth classification [21], the following fraction sizes were distinguished: coarse sand (1.0–0.5 mm), medium sand (0.5–0.25 mm), fine sand (0.25–0.125 mm), very fine sand (0.125–0.063 mm), silt (0.063–0.04 mm), clay (less than 0.04 mm).

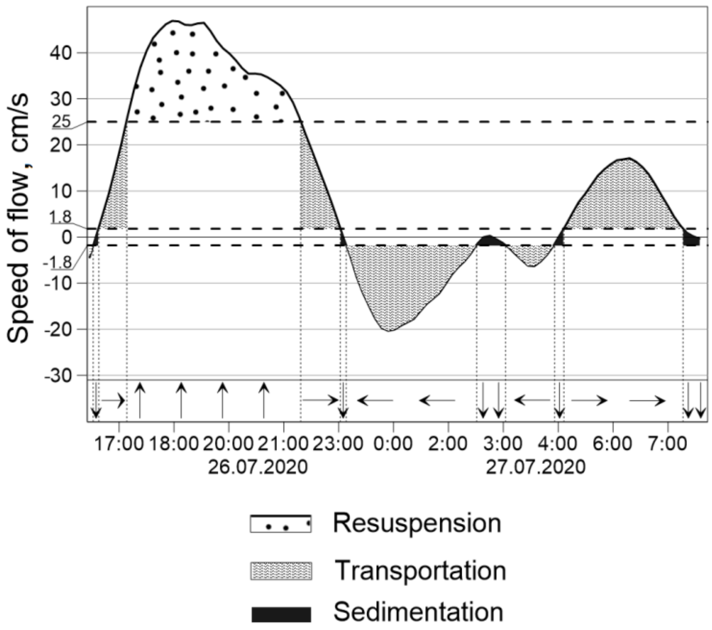
The **flow measurements** were carried out in the water area of the Vistula Lagoon adjacent to the Strait of Baltiysk at seven points (points *1–7* in Fig. 2) by autonomous current-meters – inclinometers. They were developed at the AB IO RAS by a group managed by V.T. Paka [22] to measure bottom flows in the velocity range of 0.03–0.56 m/s (with a maximum relative error of 25 % for low velocities and 3–5 % for high velocities). The measurements were carried out in the following periods: winter 24.12.2019 – 13.02.2020 (51 days), spring 17.03.2020 – 21.04.2020 (35 days), and summer 28.06.2020 – 02.08.2020 (35 days).

The measurement data were preliminarily reduced to the same step with a discreteness of 1 measurement per 10 min, then the vector values of the flow velocities were converted into scalar ones: the vectors of the flow velocities ($\overline{V_a}$) were projected onto the OX axis, whose orientation was determined based on the idea of a bidirectional (outflow and inflow) nature of the flow in the water area close to the strait [23, 24]. Rather high correlation values were obtained between the flow velocities ($\overline{V}$) at different measurement points (see Table 1).

Conditions of the suspended matter transport. The sediment movement process can be represented as a sequence of three conditional phases – resuspension, transport and sedimentation (Fig. 3). Conditional flow velocity thresholds at which these phases arise can be obtained (Table 2) from the Hjulstrøm diagram [25]. On the basis of the obtained velocity ranges, according to the flow measurements, the intervals of the phases of resuspension, transport, and sedimentation for the grain size dimensions of sands, silt and clay (according to the Wentworth classification) were identified. Those phases of potential sedimentation and transport that were not supported by the previous phases of resuspension were not taken into account. The intervals obtained for the movement of suspended sediments were converted into percentages of the total duration of measurements separately for outflows and inflows. Their comparison makes it possible to integrally estimate the conditions of suspended matter transport in the case of reciprocating flows present in the study area.

Table 1. Correlation coefficients between flow velocities ($\overline{V}$)

Measurement period	Measurement point number	Correlation coefficient
24.12.19 – 13.02.20	*1 / 2*	0.99
17.03.20 – 21.04.20	*5 / 6*	0.99
28.06.20 – 02.08.20	*1 / 2*	0.94
28.06.20 – 02.08.20	*3 / 4*	0.92



F i g . 3 . Phases of the flow velocity at which potential resuspension, transport and sedimentation occur for particles of the grain size range 0.125–0.250 mm (fine sand). Horizontal dotted lines indicate the thresholds of resuspension and sedimentation for the selected range of grain size. Positive flow rate means inflow of water into the lagoon, negative – outflow. The arrows along the horizontal axis schematically indicate the processes of sedimentation (↓), transport (→;←) and resuspension (↑)

T a b l e 2 . Thresholds of the rate of resuspension and sedimentation according to the Hjulstrøm diagram [25] for various grain size dimensions

Sediment type (by Wentwort)	Particle size, mm	Resuspension threshold, cm/s	Sedimentation threshold, cm/s
Clay	0.040–0.063	25	0.5
Silt	0.063–0.125	20	0.9
Very fine sand	0.125–0.250	25	1.8
Fine sand	0.250–0.500	30	3.6
Medium sand	0.500–1.000	45	6.6

3. Results and discussion

Sedimentary environment. To characterize the hydrolithodynamic system of the strait, the classification widely used abroad [14–17] of sedimentary environments for estuaries was taken as a basis.

In the classification of sedimentary environments, a special type of estuaries is distinguished – a tidal estuary with a predominantly wave water exchange regime (wave estuary) [14, 17]. This type of estuaries is formed in the river–lagoon–strait–sea systems; it is characterized by the presence of a sandy barrier between the lagoon and the sea, channels (straits) through the barrier, a flooded tidal delta from the lagoonal side of the barrier, the central part of the estuary and the inner river delta.

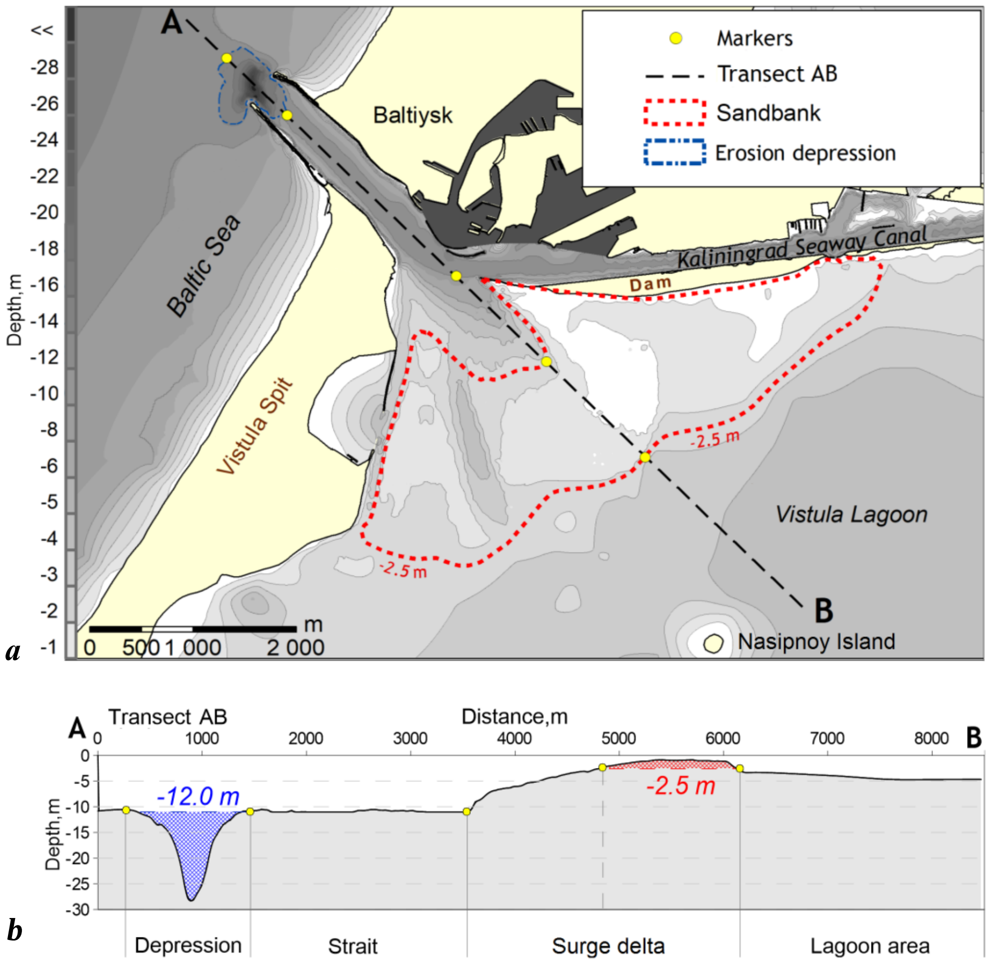
The Vistula Lagoon is a lagoon-type tideless body of water where sea and fresh waters mix; therefore, by definition [14], it can be attributed to an estuarine system. In the Baltic Sea, the tidal movements are virtually absent, but surges of various genesis are very developed, ensuring the inflow of sea water into the lagoon and, accordingly, their outflow when surge conditions disappear [13]. Together with sea waters, marine sand is brought into the lagoon, it is deposited in the immediate vicinity of the strait and forms a sand bank [5, 11].

Similarly to the conceptual model of sedimentary environments of the wave estuary [14], and also by analogy with the identification of the "inner" delta in [26], the following zones were distinguished based on morphological features in the area of the Strait of Baltiysk (Fig. 4):

– Baltic Spit and the Strait of Baltiysk – the sand barrier and passage through it;
– sand bank at the lagoon-ward end of the strait – the surge delta (by analogy with the tidal one);
– the Vistula Lagoon – the central part of the estuary.

The surge delta is a shallow, which is formed at the mouth of the strait (channel) on the side of the lagoon. According to [15, 26], such accumulative formations are mainly composed of sediments, which are intercepted from the alongshore (from the sea side) sediment flow by reciprocating water movements through the strait (in the classical version [14] they are caused by tides, and in our case – by upsurges and downsurges). That is, in the case of the Vistula Lagoon, the surge delta serves as a zone of final deposition of sand deposits during their movement from the sea to the lagoon.

Granular composition of bottom sediments. The deposits of the accumulative area of the surge delta (point *B2*) contain 51 % of medium sands and 39 % of fine sands, and the deposits of the central gully (point *B1*) contain 84.8 % of fine sands (Table 3). The shares of coarse sands and very fine sands at points *B1* and *B2* are 5 % each. The predominance of medium and fine sands in the sediments of the accumulative area of the surge delta (point *B2*) indicates that the delta is mainly fed by these fractions. In the inner part of the lagoon, at point *B3*, the sediments contain 50 % of very fine sands, 29 % of fine sands, 10 % of medium sands and 10 % of silt.



F i g . 4 . Diagram of the morphological structure of the bottom relief of the sedimentary system of the Strait of Baltiysk: plan view (*a*) and profile *AB* view (*b*)

Vertical distribution of the suspended material. The experimental sampling of the suspended material at points *2* and *7* showed a gradual decrease in the mass of the accumulated material depending on the distance from the bottom (Table 4). Such a vertical distribution can be interpolated by an exponential curve with a fairly high regression coefficient (*r* from 0.85 to 0.98) and a small standard deviation (σ within 0.3–0.6 g):

$$m = A \cdot e^{-H/H_0},$$

where *A* (g) and H_0 (cm) are the parameters of the regression dependence.

For three exposures (Table 4), the coefficients *A* and H_0 are 22.3 g and 370 cm, 9.2 g and 670 cm, 24.7 g and 230 cm, respectively. These interpolations are characterized by regression coefficients and standard deviation values: 0.98 and 0.3 g, 0.85 and 0.3 g, 0.98 and 0.6 g, respectively.

T a b l e 3 . Particle size distribution of sedimentary material and suspended sediments at points *B1*, *B2*, *2*, *7* (%)

Sampling points	Sand				Silt	Clay
	coarse	medium	fine	very fine		
Sediments taken with a VanVeen grab						
B1	1	4	85	10	0	0
B2	4	51	40	5	0	0
B3	0	19	29	50	10	0
Suspended sediments accumulated in horizontal-type traps						
2	0	0	8	39	53	1
7	0	0	5	34	61	0
Suspended sediments accumulated in vertical-type traps						
7	0	1	16	44	40	0

T a b l e 4 . The mass of the suspended material according to the results of experimental sampling (m_{mea}) and interpolation (m_{int}) at points *2, 7*

Level above the bottom, cm	Sampling method					
	Horizontal-type traps *		Horizontal-type traps **		Vertical-type traps **	
	m_{mea}, г	m_{int}, г	m_{mea}, г	m_{int}, г	m_{mea}, г	m_{int}, г
40	20.0	20.0	9.0	8.7	21.5	20.7
60	18.5	19.0	–	8.4	–	19.0
80	18.5	18.0	–	8.2	–	17.4
100	–	17.0	7.5	7.9	15.0	15.9
120	16.0	16.1	–	7.7	–	14.6
150	–	14.9	7.5	7.6	13.0	12.8
170	14.0	14.1	–	7.1	–	11.7
200	–	13.0	7.0	6.8	10.5	10.2

* Samples were taken at point *2*.

** Samples were taken at point *7*.

N o t e : the dash means samples were not taken.

Despite the difference in the duration of exposure of sediment traps at points *2* and *7* (687 and 432 hours), horizontal-type sediment traps at both points accumulated an approximately equal amount of material, which indicates a uniform distribution of the flow of suspended material over the entire area of the surge delta.

Although the characteristics of the interpolation curves describing the vertical distribution of suspended material differ at first glance, the data indicate that within the water column from the 40 cm to the 2 m level above the bottom, the amount of accumulated material varies within only 25 % of the maximum located at the 40 cm level above the bottom, which indicates a weak flow stratification along the vertical within a 2-meter water layer above the surge delta. This means that it is possible to estimate the transport from data obtained at only a few levels.

The mass of material in vertical-type sediment traps at point *7* also gradually increases from the upper to the lower levels. The characteristics of the vertical distribution are similar to those obtained for masses accumulated in horizontal-type traps. The only difference is that the mass in vertical-type traps grows faster (the values differ twice as much at the levels of 2 m and 40 cm above the bottom) than in horizontal-type traps where the difference was 1.3–1.4 times. It is natural, since the lower vertical-type traps integrate the entire vertical flow, which grows from level to level.

Granular composition of suspended sediments. According to the results of the grain size analysis of the suspended material taken into horizontal-type traps, i.e. from a horizontal flow, it was found that in summer seasonal conditions above the surge delta in a 2-meter layer from the bottom, the water flow carried 55–61 % of silty material, 34–39 % of very fine sand and 4–8 % of fine sand. Medium and coarse sands were not found in the horizontal-type traps. The sediment traps for vertical flows (vertical-type traps) accumulated 40 % of silty material, 44 % of very fine sand, 16 % of fine sand and up to 1 % of medium sand.

The silty material accumulated by the sediment traps could only be carried out of the lagoon into the sea, since it is scarce in marine sediments [27]. Very fine sands are widespread both in the sea and in the lagoon [7]; therefore, their accumulation in sediment traps (see Table 3) could be provided by both inflows from the sea and outflows from the lagoon. No medium sand was found in the sediment traps, which is consistent with the low water flow rates during the sampling period.

Estimates of the transport times of suspended material of different fractions. The summer installation of sediment accumulators did not provide sufficient information to assess the conditions for the transport of suspended material; therefore, the assessment was carried out on the basis of flow measurement data. Since a reliable relationship was found between the records of near-bottom velocities at points *1–7* (see Table 1), the water flow velocity averaged over the measurement data at these points was used to estimate the conditions for the transport of suspended matter.

At the first stage, the total time intervals of the successive phases of resuspension and transport of suspended material of different sizes were estimated, while the situations of inflow and outflow were analyzed separately, and the obtained values were converted into percentages (Table 5). The results showed that the velocity characteristics of the water flow both during inflow and outflow were sufficient for the transport of water suspension of all dimensions. Therefore, the general nature of the process of movement of suspended sediments through the strait can be expressed by the sum and difference in the durations of the potential transfer of the suspended material between inflows and outflows (Table 6).

The conditions for the transport of silt (32–54 %) and very fine sand (48–64 %) were preserved by the water flow for the longest time (as a percentage of the entire duration of the measurement), then, as the size increased, the duration of the transport of fine sand (32–44 %), medium sand (17–34 %) and coarse sand (1–3 %) followed (Table 6).

If we consider the movement of sediments through the strait as a reciprocating (or alternating) movement of material from the sea to the lagoon and back to the sea, then the difference in the duration of the transport of suspended material during inflows and outflows will characterize the balance of movement of suspended sediments through the Strait of Baltiysk in the period under consideration (Table 6).

Depending on the characteristics of the water flow, the silt and sandy material can be transported both from the lagoon to the sea and from the sea to the lagoon, but the possibility of involving the silt already carried into the sea is unlikely, since it is carried away by the alongshore flow. The velocity conditions for the transport (Table 6) of very fine sand were longer in winter and spring during outflows (by 8.1 and 0.2 %), and in summer – during inflows (by 2.4 %). The possibility

T a b l e 5 . The duration (in hours) of successive phases of resuspension and transfer of suspended sediments of different grain size according to flow velocity in the winter, spring, summer measurement periods (% is indicated from the total duration of measurements)

Sediment type	Winter (687 h)				Spring (432 h)				Summer (432 h)			
	Inflow		Outflow		Inflow		Outflow		Inflow		Outflow	
	h	%	h	%	h	%	h	%	h	%	h	%
Coarse sand	0	0	0	0	0	0	0	0	0	0	0	0
Medium sand	0	0	0	0	8	1	11	2	10	1	0	0
Fine sand	49	10	54	11	98	16	105	17	69	10	50	7
Very fine sand	101	21	91	19	140	23	121	20	115	17	102	15
Silt	130	27	131	27	167	28	215	36	175	25	158	23
Clay	101	21	91	19	134	22	189	31	116	17	104	15

T a b l e 6 . The sum of and the difference in the duration (% of the total measurement duration in hours) of the potential particle transport of various sizes in the time interval between inflows and outflows

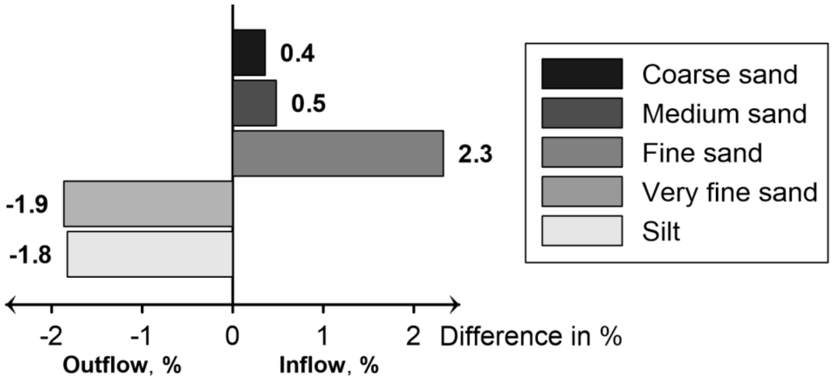
Sediment type	Winter		Spring		Summer	
	Sum	Difference	Sum	Difference	Sum	Difference
Coarse sand	0	0	0	0	0	0
Medium sand	40	2	54	–9.1	32	1.8
Fine sand	54	–0.2	64	–8.1	48	2.4
Very fine sand	40	2	44	3.2	32	1.8
Silt	21	–0.9	34	–1.2	17	2.9
Clay	0	0	3.2	–0.6	1.4	1.4

of transporting fine sand lasted longer in winter, spring, and summer, and only during inflows (by 2, 3.2, and 1.8 %, respectively); medium sand – during inflows in winter and spring (by 0.9 and 1.2 %), and in summer – during outflows (by 2.9 %). Velocity conditions for the transport of coarse sand were noted only in spring and summer, while in spring the balance turned out to be in favor of outflows (by 0.6 %), and in summer – in favor of inflows (1.4 %).

In total, over all three measurement periods (73 days), the velocity conditions for the transport of silty material and very fine sand were longer during outflows (by 1.8 and 1.9 %), and fine, medium and coarse sands – during inflows (by 2.3, 0.5 and 0.4 %, respectively) (Fig. 5). It follows from this that during the flow measurements, the surge delta potentially accumulated material. To a greater extent, it was fed by fine sand, to a lesser extent, by medium and coarse sands.

4. Concluding remarks

The measurements carried out illustrated the features of the process of sediment transport through the Strait of Baltiysk in certain periods of the year. The *in situ* data on the accumulation of suspended material in traps made it possible to conclude that there is a slight vertical stratification of horizontal flows of suspended material (the values at the levels of 2 m and 40 cm above the bottom differ by 1.3–1.4 times). Due to the impossibility of covering all seasons of the year with direct observations, and also since the region under study is a transit region, the estimated difference in the duration of the potential transport of suspended material (according to the measured flow velocities) enables us to make assumptions about its general nature. The silty material is transported from the lagoon to the sea. The transfer of very fine sand is characterized by reciprocating motion. It can both be carried out and brought back into the lagoon, while very fine sand is not deposited on the surge delta, which



F i g . 5 . Balance characteristic of the movement of suspended sediments through the Strait of Baltiysk: the difference in the total duration (%) of the suspension transfer between the inflows and outflows during three measurement periods (negative values – predominance of the outflow, positive ones – predominance of the inflow). Measurement duration was 73 days (100 %)

is the zone of final deposition for larger fractions. Surge delta deposits consist mainly of fine and medium sand with an insignificant content of coarse sand; their source is the alongshore sediment flow (from the seaward part of the Baltic Spit). The movement of sand of these dimensions is characterized as reciprocating, therefore, at a high intensity of water exchange, the sediments of the surge delta can again be involved in transport and carried back to the sea.

The low content of fine and medium sand in sediment traps corresponds to the fact that during the summer period of measurements, the water flow velocities sufficient for the mass transport of this type of suspended material were not observed.

The surge delta in the Vistula Lagoon, which is typical for the sedimentation situation in the sea-strait-estuary system, is increasing, but the current growth rate is so low that it does not explain the current size of the delta. The low rates of its development at present can be associated with regular dredging in the strait – the main flow of marine sediments is extracted during dredging at the approaches to the delta, which serves as the zone of final deposition.

Adhering to the indicated conceptual model of the sedimentary environment of the wind induced estuary, we can assume the following: if the surge delta actively develops further, then as it grows, it will increasingly clog the passage from the sea to the lagoon, and the flow of bottom sediments will be sent to the Kaliningrad Seaway Canal.

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Submitted 29.08.2022; accepted after review 20.09.2022;
revised 02.11.2022; published 23.12.2022

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All the authors have read and approved the final manuscript.