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HYDROPHYSICAL PROCESSES

Turbulent Viscosity and Flow Resistance in Tidal Estuaries

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Abstract—Field hydrometric studies at the estuaries of the White Sea basin yielded data on some hydrodynamic features of reverse tidal currents. Among the mouth areas of tidal rivers studied in 2015–2022, the most interesting results were obtained at the mesotidal Kyanda estuary, flowing into Onega Bay, and at the macrotidal Syomzha estuary, flowing into Mezen estuary. The essence of the method used in the field studies is synchronic measurements of water flow by acoustic Doppler profilers and water levels by autonomous barometric recorders in two cross-sections, located at different distances from the river mouth, during an entire semidiurnal tidal cycle. The results of these measurements were used to evaluate the terms of Saint-Venant equation of motion and the roughness coefficients. It was found that in the tidal rivers, the flow resistance varies considerably during a tidal cycle. In periods of quasi-steady water flow in both directions during flood and ebb, the values of the Darcy–Weisbach friction factor are 0.04–0.07, as is typical for rivers with similar morphological channel pattern and characteristics. However, in several cases, in periods close to slack water, the friction factor took negative values. A possible explanation of this phenomenon is a negative turbulent viscosity, which manifests itself in some phases of the tidal cycle, when the energy of eddy formations can be transferred to the translational motion of the water mass.

Keywords: reversing currents, the White Sea, tidal cycle, flow resistance, energy dissipation, turbulent viscosity, estuary

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INTRODUCTION

Since the time of Isaak Newton, the resistance force between layers of moving water (fluid friction) has been expressed in terms of the shear stress τ, taken to be proportional to the velocity gradient u in the direction perpendicular to the direction of motion y:

$$\tau = \rho\nu\frac{du}{dy}, \quad (1)$$

where ρ is water density, ν is kinematic viscosity coefficient, which, in the case of laminar water motion, is constant (depending only on the temperature and having an order of 10^{-6} m^2/s).

In the late XIX century, J. Boussinesq [28] analyzed O. Reynolds equations for turbulent flows [33] and proposed to express the covariation moments of velocity component pulsations $\overline{u_i'u_j'}$ in terms of the turbulent viscosity coefficient ν_t similarly to the coefficient of laminar (molecular) viscosity in formula (1):

$$\tau = -\rho\overline{u_i'u_j'} = \rho\nu_t\frac{du}{dy}. \quad (2)$$

In this case, the value of ν_t is several orders of magnitude greater than the value of laminar viscosity and characterizes the regime of flow, rather than the fluid itself [25].

In the practical hydraulics, fluid friction is characterized by flow resistance, which is commonly expressed in terms of empirical coefficients relating the mean flow velocity u with the friction slope I_{fr} (also referred to as a hydraulic slope), the values of which in the case of uniform motion correspond to the geometric slope of the water surface:

$$I_{\mathrm{fr}} = \frac{u^2}{C^2R} = \frac{n^2u^2}{R^{4/3}} = \frac{\lambda u^2}{8gR}, \quad (3)$$

where C is Chezy coefficient; n is Manning roughness coefficient; λ is dimensionless Darcy–Weisbach friction factor; g is gravity acceleration; R is the hydraulic radius of the flow, which is close in value to the mean depth h (in the absence of ice cover).

A relationship between the turbulent viscosity, expressed in terms of the mean value of the turbulent exchange coefficient over the vertical $A = \rho\nu_t$, and the flow resistance was proposed by V.M. Makkaveev [12], based on the analysis of velocity distribution over the vertical for natural channel flows:

$$A = \frac{\rho g h u}{2mC}, \tag{4}$$

where m is a parameter equal to 24 according to Bazen or 22.3 according to Boussinesq [9].

The values of the kinematic viscosity coefficient ν in (1) are always positive, which has a rigorous thermodynamic substantiation [19, 22]. However, in the opinion of A.S. Monin [18], the direct transfer of such an interpretation to turbulent flows is incorrect and the viscosity coefficient ν_t can take both positive and negative values, depending on the features of the mechanism of kinetic energy transfer into thermal energy (dissipation).

In a turbulent flow, the dissipation of energy commonly takes place through its passage from the averaged motion to the largest turbulent eddies and then to smaller vortices, and so on, until the eddy dimensions becomes commeasurable with the sizes of molecules and the mechanical energy starts to pass directly into heat [10, 13, 19, 20, 22, 25]. In such order of energy transfer (called the Kolmogorov cascade), the turbulent viscosity is positive; however, if this order is violated, the coefficient of turbulent viscosity can also take negative values [23].

THE HISTORY OF THE QUESTION OF NEGATIVE VISCOSITY

The assumption regarding the possibility of inverse passage of the energy from the eddies to the translational motion of water mass was made by Forchheimer in the first half of the 20th century [26]: the averaged flow may not only turn into heat and vortices; it is possible that a decrease in eddy energy may lead to an acceleration of the averaged motion; however, there are no experimental data to support this. In the following decades of the XX century, such assumption was accepted in some theoretical aero- and hydrodynamic studies in different countries [22, 29, 30]; however, the opposite point of view was also recognized by leading researchers of that time [3, 9].

The analysis of manifestations of negative viscosity in present-day gas- and hydrodynamic experiments, carried out by L.I. Vysotskii, a professor of the Saratov State Technical University (SSTU) [4], allowed him to conclude that the results of the recent high-accuracy measurements of the distribution of averaged velocities in tubes and in the boundary layer on a flat plate provide a direct evidence in favor of the existence of a layer with negative viscosity, which is a direct confirmation of this fact. This line of studies into the negative viscosity continues to develop in SSTU [5, 8].

As applied to large-scale processes, the phenomenon of negative turbulent viscosity is considered in more detail in the book of V. Starr (Massachusetts Institute of Technology) [23] with a foreword to its Russian issue by A.S. Monin [18]. Being a meteorologist, V. Starr studied in detail the effects of negative turbulent viscosity mostly in atmospheric processes, not only in the atmosphere of the Earth, but also of the Sun, Jupiter, and Saturn, as well as for spiral galaxies and the circumsolar nebula. In practical applications of the dynamic meteorology, the transfer of the vortex energy to translational motion and negative viscosity are also admitted [14, 27].

In the hydrodynamic aspects, V. Starr considered questions associated with oceanic circulation and Gulfstream meanders. Forecasting the sites of possible manifestation of negative viscosity, he notes: "...the effects of negative viscosity cannot dominate in a steady-state regime, because the entire kinetic energy of irregular motions would be quickly exhausted." In this case, to maintain a quasi-stationary regime in a system with a predominant effect of negative turbulent viscosity, two conditions are necessary: (a) the irregular motions that transfer the momentum against the gradients of the average flow must have a source of turbulent kinetic energy...; (b) the average flow must be counteracted by some type of retardation so as not to increase indefinitely [18].

These conditions are almost ideally met in tidal estuaries; however, V. Starr in [23] mentions them only indirectly in the context of the analysis of tidal currents. Under certain conditions, tidal currents may change the direction of the gradient of average flow to inverse, while the direction of momentum transfer remains downstream, thus creating an effect of negative viscosity.

The possible manifestation of negative turbulent viscosity at the Onega estuary is mentioned in [6]. Debolskii et al. analyzed the transformation of the diagram of vertical velocity distribution during the tidal cycle under an ice cover and found that, twice during the tidal cycle, the turbulent exchange coefficient (the product of the coefficient of turbulent viscosity and water density) takes negative values. Analyzing this fact, the authors make a very cautious conclusion: the effect of negative viscosity in itself is common in turbulent processes with imposed external wave disturbances [a reference to 23]; however, we cannot definitely say that this is natural in our case, because it is impossible to check its statistical reliability due to the lack of a statistical ensemble. Therefore, now we should only keep in mind the possibility of the appearance of negative values of the coefficient of turbulent exchange in the under-ice tidal current.

In 2015–2022, detail hydrometric measurements were carried out at the tidal estuaries of the White Sea basin (the Northern Dvina, Onega, Mezen, as well as the small rivers Kyanda, Tamitsa, Syomzha, and Laya) during expeditions of the Department of Land Hydrology, Faculty of Geography, Moscow State

University, with the use of the modern hydrological and geodesic instruments [2, 24, 32]. Originally, their objective was to collect data for hydrodynamic simulation [11, 21] and to solve particular hydroenvironmental problems [15, 16]. However, a detail analysis of the values of the terms of Saint-Venant equations in the case of reverse motion of water masses in the estuaries of the small rivers of Kyanda and Tamitsa revealed, at first glance, a paradoxical phenomenon—strong variability of the hydraulic resistance during the tidal cycle up to its negative values [1, 2].

The accumulation of observation data, the extension of the geography of studies, and the improvement of the study procedure [32] has led to the conclusion that this result is not due to measurement errors. A hypothesis, under which the phenomenon of variations of the flow resistance and its negative values can be considered, can be the assumption of the negative turbulent viscosity manifistation, which appears in reverse water flow in some phases of the tidal cycle.

Since the hydraulic resistance reflects the loss of energy by water flow, its variations during the tidal cycle can be explained by the proportions of the parts of water flow with direct and inverse transition of energy by Kolmogorov cascade. When the direct transition of the energy of translational motion into eddy energy and further to the heat dominates, the resistance is positive. When the eddy energy return exceeds the dissipation, the resistance becomes negative: instead of a loss of energy by the averaged motion, it is charged with pulsation energy.

Under certain combination of the tidal flow and river runoff, such situation was observed (and recorded instrumentally) on the Kyanda, Tamitsa, and Syomzha within 0.5–1.5 h after the moment of high water, when the velocity of ebb current increased at a practically horizontal water surface [1, 2, 32].

MATERIALS AND METHODS

Under one-dimensional schematization, the reversing current in the tidal reach of a river can be described by Saint-Venant equations with the equation of motion written as

$$-\frac{\partial z}{\partial x} = \frac{\alpha_0}{g}\frac{\partial u}{\partial t} + \frac{\alpha u}{g}\frac{\partial u}{\partial x} + \frac{h}{2\rho}\frac{\partial \rho}{\partial x} + \frac{\lambda u|u|}{8gh}, \qquad (5)$$

here x is the longitudinal coordinate along the dynamic axis of the flow, directed toward a sea; t is time; z is free surface elevation; α_0 is Boussinesq coefficient (corrective of kinetic energy); α is the Coriolis coefficient (corrective of momentum).

The left part of equation (5) is the geometric slope of the water surface $I = -\frac{\partial z}{\partial x}$. The first term on the right side $\frac{1}{g}\frac{\partial u}{\partial t}$ characterizes local acceleration, and the second term $\frac{u}{g}\frac{\partial u}{\partial x}$, the convective acceleration (they are called *inertial terms*). The density term $\frac{h}{2\rho}\frac{\partial \rho}{\partial x}$ is taken into account when salt seawater enters the tidal reach of the river and creates a longitudinal gradient of water density; if this does not take place, it is neglected.

The fourth "friction" term in the right part of equation (5) is the friction slope I_{fr}, which is commonly expressed by a formula of the type (3), where the square of the mean velocity is replaced by the product of the velocity and its module to ensure that the friction force acts in the direction opposite to the direction of flow [17, 31]:

$$I_{fr} = \frac{\lambda u|u|}{8gR}. \qquad (6)$$

This approach to the parametrization of the hydraulic resistance is based on the assumption that, in the case of unsteady water flow, it will be the same as in the case of a uniform flow, under the same flow velocity, depth and bottom roughness.

The use of the coefficient of flow resistance λ in equation (5) and formula (6) (instead of the Chezy and Manning coefficients, which are much more popular in river hydraulics) is due to the fact that, in the case of different signs at the velocity and friction slope in formulas of the type (3), only it can take negative values.

The friction slope is calculated from equation (5) as the difference between the geometric slope (the left side) and other terms on the right side of the equation. The coefficient of flow resistance is calculated using the obtained values of friction slope by formula (6).

For an approximate estimate of the coefficient of turbulent viscosity, the relationship (4) is transformed for reverse flows to the form that makes it possible to obtain negative values of ν_t at negative values of λ:

$$\nu_t = 0.025h|u|\frac{\lambda}{\sqrt{|\lambda|}}. \qquad (7)$$

In this case, the replacement of coefficient C by λ was carried out based on relationship (3).

The values of all terms of equation (5), except for the friction term, can be evaluated directly based on high-accuracy field data. To do this, synchronous measurements of water level and discharge (average flow speed), as well as water TDS and temperature are to be carried out at two cross-sections at different distances from the river mouth [1, 2, 32]. The use of acoustic doppler current profiler (ADCP), combined with autonomous barometric water level loggers, can provide the accuracy of calculations required for the analysis as applied, at least, to small rivers. At the small estuary, the passage of a cross-section by a vessel with ADCP takes 3–5 min, which allows the measurement result to be taken as an instantaneous value of water

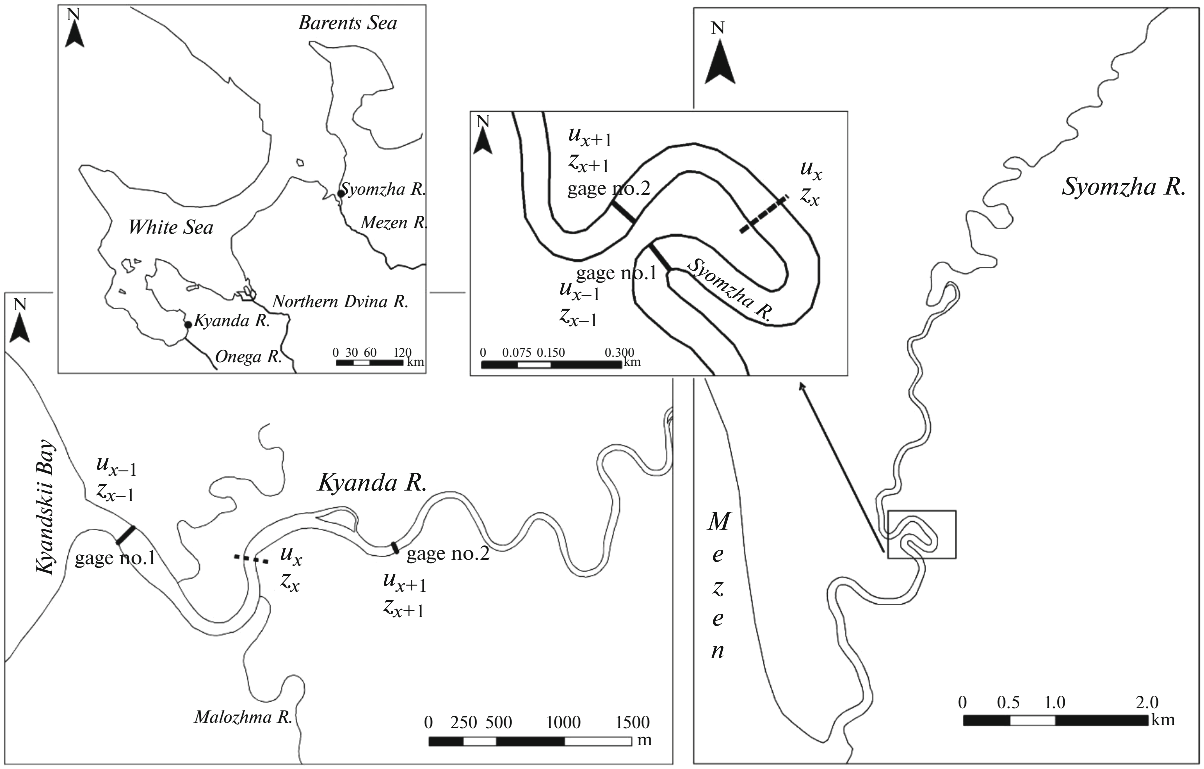

Fig. 1. Schematic map of the study objects—the rivers of Kyanda and Syomzha.

discharge and average flow velocity. (The possibility of such an assumption for larger rivers is still questionable, because at the channel width of several hundred meters or more, the time of water discharge measurement may be comparable with the duration of individual phases of semidiurnal tidal cycle, including the processes of flow direction change at high and low water).

Among the tidal estuaries of the White Sea basin studied in 2015–2022, the most interesting results were obtained at the mesotidal Kyanda estuary, emptying into Onega Bay of the White Sea [1, 2], and at the macrotidal Syomzha estuary, emptying into the Mezen estuary [32] (Fig. 1).

These small rivers flow under similar enviremental conditions, which determine the features of their water regime. The high snow-melt spring flood is ussualy replaced by summer low-water season. Maximal water discharges in the Kyanda are commonly recorded in early May, and those in the Syomzha, in the middle or late May. The summer–autumn low water season begins in June and ends in November; the lowest discharge is commonly observed in August, when the measurements were made. As the result, the tidal flood and ebb water discharges during low-water season are 1–2 orders of magnitude higher than their runoff values (Table 1).

Detail measurements of water levels and discharges for evaluating the terms of the equation of motion were carried out in the Kyanda and Syomzha estuaries during summer low water seasons in 2016 and 2018, respectively. The height of the tide in the observation period at the mouth sections reached 2.2 m in the Kyanda and 7.0 m in the Syomzha. In the Kyanda in 2016, the lower gage corresponded to the mouth section and the upper one was located 2.8 km upstream. In the Syomzha in 2018, the distance between the gages was 0.9 km (3.6 and 4.5 km upstream of the mouth section). The study segment was chosen within an omega-shaped bend of the Syomzha channel in order to ensure the best agreement between the logger zeros in the upper and lower gages (it is possible to align the levels from one station at a width of the meander neck <100 m).

The salinity and, accordingly, the density of water in the Syomzha in the upper and lower gage varied practically synchronously, because of which, the density slope throughout the period had no effect on the friction slope. In the Kyanda, two peaks of the density gradient were recorded between the gages during the tidal cycle (Table 1); therefore, the density gradient was taken into account in the calculation of the friction slope and the flow resistance factor.

The terms of the equation of motion (3) were calculated with the use the finite-difference scheme (5–8) similar to that used for numerical solution of partial differential equations (Fig. 2). Under such schematization, the obtained values of hydrodynamic charac-

Table 1. Main hydrodynamic characteristics of the Syomzha and Kyanda estuaries based on data of measurements during the summer low-water season in 2015–2018

Characteristic	Measurement units	Syomzha	Kyanda
The highest measured value of tide in the mouth section	m	7.0	2.2
Maximal measured flood discharge (toward the river) in the mouth section	m^3/s	–280	–138
Maximal measured ebb discharge (toward the sea) in the mouth section	m^3/s	245	85
Measured river runoff	m^3/s	5	5
Mean river slope	‰	0.61	1.9
Mean river slope in its lower reaches	‰	0.26	0.2
Measured distance of high tide penetration (of tidal variations of water level)	km	21–22	10
Measured distance of reverse currents	km	>12	8
Measured distance of salt water intrusion	km	12	6.5
Maximal TDS in the mouth section	PSU	18	20
The range of density variations in measurement sections	kg/m^3	1000–1010	1000–1016

teristics can be associated with a gage located half-way between the measurement gages. Accordingly, linear interpolation of the hydraulic characteristics of the flow and the morphometric characteristics of the channel between gages was assumed acceptable (which was confirmed by the data of measurement operations). The calculation step in the spatial direction Δx was taken equal to half the distance between the measurement gages. The mean time step Δt was chosen in accordance with the propagation speed of the high tide wave $\frac{\Delta x}{\Delta t}$ and, based on the results of field observations, was taken equal to 15 min.

The changes of flow velocity over time for the calculation of local acceleration was calculated as

$$\frac{\partial u}{\partial t} \approx \frac{u_{x+1}^{t+1} + u_{x-1}^{t+1} - u_{x+1}^{t-1} - u_{x-1}^{t-1}}{4\Delta t}, \tag{8}$$

here, $(u_{x+1}^{t+1} - u_{x+1}^{t-1})/2\Delta t$ corresponds to changes in the flow velocity at the upstream gage over 30 min, and $(u_{x-1}^{t+1} - u_{x-1}^{t-1})/2\Delta t$, to changes at the downstream gage.

The flow velocity along the channel for determining the convective acceleration was calculated in a similar way:

$$\frac{\partial u}{\partial x} \approx \frac{u_{x-1}^{t-1} + u_{x-1}^{t+1} - u_{x+1}^{t-1} - u_{x+1}^{t+1}}{4\Delta x}, \tag{9}$$

$(u_{x-1}^{t-1} - u_{x+1}^{t-1})/2\Delta x$ corresponds to changes in flow velocity between the gages in the lower time layer

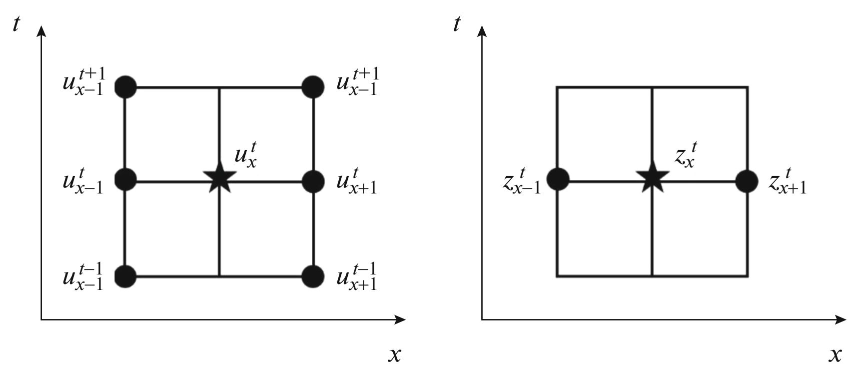

Fig. 2. Calculation scheme of the terms of the equation of motion.

$(t-1)$; and $\left(u_{x-1}^{t+1}-u_{x+1}^{t+1}\right)/2\Delta x$, at the upper time layer $(t+1)$.

The mean flow velocity was also determined using four measured flow velocities

$$u=\frac{u_{x+1}^{t}+u_{x-1}^{t}}{2}. \quad (10)$$

The slope of the water surface at time t was calculated using water levels at the downstream and upstream gages:

$$\frac{\partial z}{\partial x}\approx\frac{z_{x-1}^{t}-z_{x+1}^{t}}{2\Delta x}. \quad (11)$$

A similar difference was used to evaluate the density term. The Boussinesq and Coriolis coefficients were calculated based on the analysis of the flow velocity field at a cross-section, obtained with the use of ADCP during water discharge measurement.

Thus, the data of field measurements were directly used to evaluate the terms of the equation of motion (5), corresponding to the local and convective acceleration, as well as the density term and the water surface slope. The friction slope $I_{\rm fr}$ was determined as their difference in accordance with equation (5). The obtained values of $I_{\rm fr}$ were used to evaluate the Darcy–Weisbach friction factor by formula (6) and the corresponding values of the turbulent viscosity coefficient, by formula (7).

RESULTS AND DISCUSSION

The maximal absolute values of the geometric slope (both direct and reverse), as well as the friction slope were recorded in both rivers during periods of quasi-steady flow at flood and ebb [2, 32]. In the Syomzha, they were of the order of 10^{-4}, and on the Kyanda, of 10^{-5}. Conversely, the values of the inertial terms reached their maximums (of the order of 10^{-6}–10^{-5}) at an acceleration or deceleration of currents. The density term for the Syomzha was of the order of 10^{-7}–10^{-8} for the major portion of the tidal cycle, and it is only in the beginning of the tidal level rise that it increased to 10^{-6}, though remaining several times less than the inertial term. In the Kyanda, the change in the order of the density slope was from 10^{-8} to 10^{-6}, which is comparable with the variation range of the convective acceleration.

The flow resistance was found to vary widely during the tidal cycle (Fig. 3). The friction factor λ varied from –26.0 to 20.0 in the Kyanda and from –0.13 to 0.52 in the Syomzha. In periods of quasi-steady water flow, both at flood and ebb, the values of the friction factor varied within 0.04–0.07. The range of the values of Manning roughness coefficient n, corresponding to such values of λ, is 0.015–0.030 at a flow depth typical of those rivers. This is fully true for common rivers with similar morphological characteristics of the channel pattern.

The most atypical values of the flow resistance were recorded at the moments of changes in flow direction. At the turn of currents, the flow resistance coefficient first abruptly increased and then, within 0.5–1.5 h, abruptly dropped. Negative values after change in the direction of currents were recorded for both the Kyanda and the Syomzha, and the initial evaluation of possible calculation errors associated with instrumental measurement error did not reject these values [32].

During the tidal cycle, the turbulent viscosity $\nu_{\rm t}$ varied from –0.006 to +0.020 m^2/s in the Syomzha, and from –0.0026 to 0.0054 m^2/s in the Kyanda. The obtained extreme values in the variations of turbulent viscosity coefficients are 3–4 orders of magnitude greater than water molecular viscosity, which is in good agreement with the conventional estimates [25].

In the study of the relationship between the negative hydraulic resistance and the negative turbulent viscosity, it is necessary to consider the proportions of the parts of water flow with energy transfer in the direct and inverse directions of the Kolmogorov cascade. If the pulsation energy turns into heat and returns to the averaged flow in equal proportions, then the total flow resistance of the transit flow is zero; if the return exceeds dissipation, then the resistance becomes negative: instead of a loss of energy by the averaged motion, it is recharged by pulsation energy, and the speed of the averaged flow increases.

The negative values of the flow resistance, observed after the slack water in the Kyanda and Syomzha, indicate the predominance in the flow of a reverse transfer of the energy of eddy formations into the energy of forward motion of the water mass. High-accuracy flow measurements show that, during ebb flow beginning, the flow velocity in both sections, after the turn of the flow, gradually increases over time in the absence of a seaward slope of water surface (Fig. 4).

At a horizontal free surface of the estuary, the gravity force cannot be the moving force transporting water masses seaward, as is the case in normal rivers in the presence of water surface slope. There was no wind during the measurements, the force of hydrostatic pressure resulting from the density difference between the river and sea water was negligible and, moreover, acted in the direction opposite to the accelerating ebb current. A force that can accelerate the motion of the water mass could be some special force that results from the release of eddy energy at its reverse transfer to translational motion and is formally reflected in the negative values of the friction slope and hydraulic resistance.

Analyzing the nature of flow resistance in connection with fluid viscosity, M.A. Velikanov [3] wrote that it is the process of transition of mechanical energy into

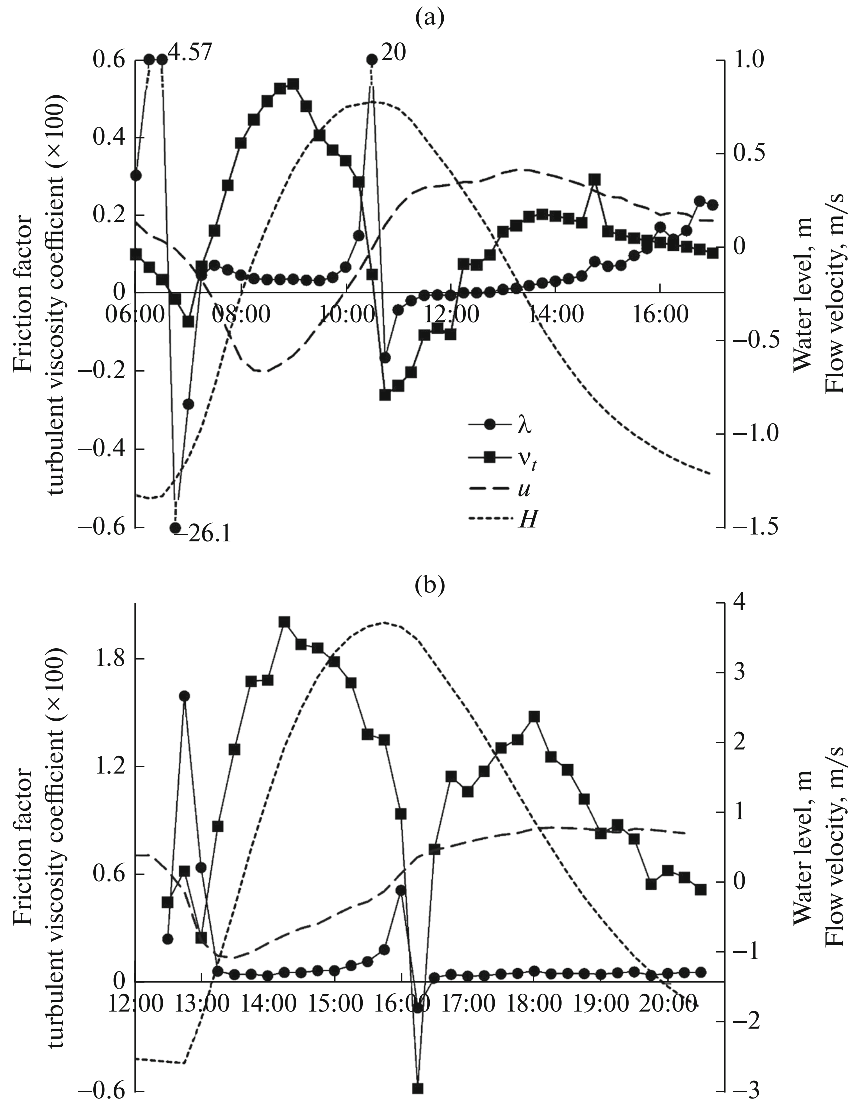

Fig. 3. Variations of the friction factor λ, turbulent viscosity coefficient ν_t, mean flow velocity u, and water levels during the tidal cycle: (a) in the Kyanda R. on August 4, 2016; (b) in the Syomzha R. on 14.08.2018.

heat, in other words, energy dissipation, that is the source of flow resistance, which has to be taken into account when solving many practical problems. Further, discussing the vortex structure and the displacement of some small volumes of liquid in turbulent flow, he says that we can replace these irregular motions by their statistical effect, namely, some special forces analogous to viscosity forces. Therefore, he considers the turbulent viscosity as a source of some special force, although analogous, but not identical in its nature to the molecular friction force, which determines the positive values of the roughness coefficients within the framework of the commonly accepted parameterization of the friction slope.

The proposed scheme of the possible energy redistribution in the reverse flow also makes it possible to interpret the fact that the coefficients of turbulent viscosity and flow resistance take on their greatest values immediately before the reversal of the flow. This reflects the intense transition of the energy of the averaged motion to the eddy motion, and, after the turn of the flow, the energy accumulated in the vortices is released and transfers back into the average motion of the water mass.

The results of hydrometric measurements in tidal reaches of rivers were also confirmed by the results of visual observations of the character of flows: in the process of measurements, it could be clearly seen that at the turn of the main current, the water mass does not remain motionless, but is a system of different-scale vortices chaotically moving across the water area of the mouth domain. In particular, traces of foam are clearly visible in Fig. 5, outlining large vortices with contours similar to meanders. After the start of the

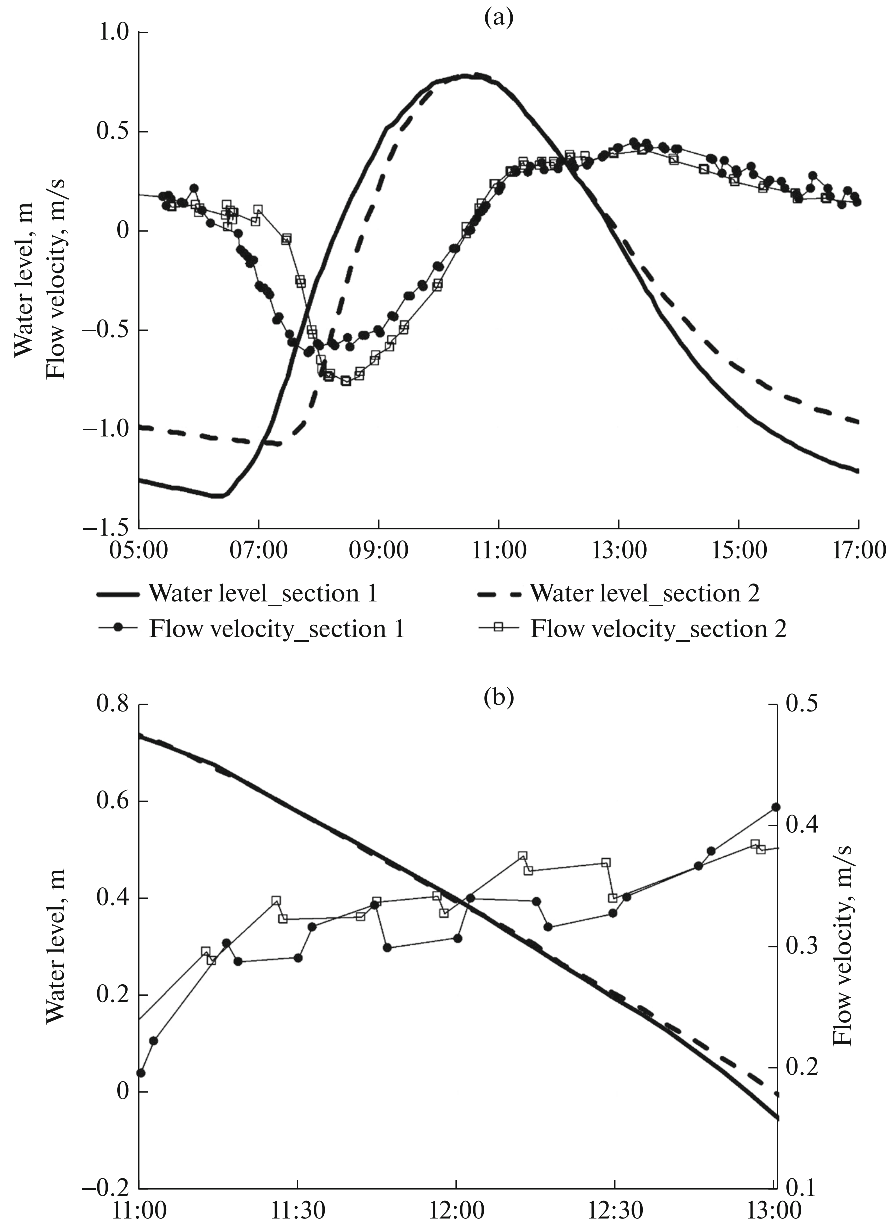

Fig. 4. Variations of the mean flow velocity and water levels in the Kyanda R. on August 4, 2016: (a) during the tidal cycle; (b) at ebb current from 11 to 13 UT.

ebb, the vortices acquired some order, forming an accelerating transit current toward the sea.

CONCLUSIONS

The presented results of the field data analysis for the tidal rivers of the White Sea basin demonstrate strong variations of the flow resistance during the tidal cycle: it increases before the turn of the current and next abruptly decreases down to negative values. A possible explanation of this phenomenon is the inverse transfer of the eddy motion energy to translational motion, resulting in the formation of negative turbulent viscosity, similar to what happens in the ocean [7].

At the same time, it should be understood that the negative viscosity is (unfortunately) not a useful phenomenon, such as superconductivity or superfluidity, but just a quirk of the parameterization of fluid friction, accepted since the time of Newton. The validity and expediency of the introduction of the concept of turbulent viscosity for expressing Reynolds turbulent stresses is still a controversial issue [5], though this approach has been used to solve practical problems for more than a century.

Fig. 5. Water surface in the tidal reach of the Kyanda R. at the moment of slack water.

At the same time, the correct specification of the parameters of turbulent viscosity and flow resistance, which depends on it, is a condition for correct modeling of tidal currents. From the practical point of view, this is of importance at the power, recreation, and water-transport use of the estuarine areas of Russian rivers. Taking into account that almost all rivers of the Russian Arctic, because of the small slopes at their mouths, should be considered tidal in their modeling, and the observed effects are to be taken into account. In addition, tidal estuaries are unique natural laboratories for studying the interaction between the vortical and translational motion of water masses, which take place not only in tidal rivers, but also in the World Ocean.

It should be mentioned that the predominance of a reverse transfer of energy from the eddies to translational motion in tidal estuaries manifests itself only in the case of a certain "favorable" combination of the parameters of river runoff and sea tide. Criterial estimates of the range of the detected hydrodynamic effects can be made after the accumulation of high-accuracy materials of field studies.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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