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Hydrodynamics of the Onega River tidal estuary as a basis for ecosystem monitoring

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Abstract. Tidal river mouths are very complicated objects for hydrological and ecosystem research. Moreover, river mouth areas are characterized by unique and vulnerable ecosystems with great biodiversity. Water quality and hydrological monitoring is essential for their preservation in conditions of intensive water use. We provided comprehensive field observations of the flow dynamics in the Onega River estuary during winter and summer period. Field data analysis has shown flow velocity and flow direction variability over a tidal cycle and depending on river runoff, wind conditions and ice cover. We investigated flow velocity profiles and cross-section velocity distribution over a tidal cycle. Also, water levels and salinity were measured over a tidal cycle at multiple locations along the estuary. All the collected data can be used for designing an ecosystem monitoring program and setting up a hydrodynamic model of the Onega River estuary.

1. Introduction

Estuaries are vulnerable and specific water bodies which strongly differ from inland and marine ecosystems by biotic and non-biotic conditions. Ecosystem monitoring is often being conducted without taking all specific features of hydrological conditions into account. Tides may cause river current change from direct down through river bed to reverse that leads to volatile regime of dissolved and suspended material fluxes. Tidal estuaries in Russia are located within basins of the White and the Barents Seas and also in Far East region. Roshydromet hydrological gauging network in tidal estuaries is sparse and weak. Most part of observations are water level, temperature and salinity measurements few times a day. Flow velocity measurements are made very rarely.

Onega River estuary is one of the typical tidal estuaries. The Onega River mouth area consists of the river part, which includes the estuary, and the shallow marine part in Onega Bay (Fig. 1). The length of the river part of the mouth area is about 26 km. It corresponds to the distance, over which tidal water level oscillation become negligible (less than 10 cm). Mean annual discharge of the Onega River is about 500 m³/s. Mean annual tidal range at the mouth cross-section is 2.38 m. Tidal curve is asymmetrical as duration of the water level decrease is higher duration of the increase. During the summer low flow period tidal wave propagates upstream with an average phase velocity of about 20 km/hour. Tidal wave height significantly decreases towards to upstream the Onega River. The intensity of this decrease depends on river flow and ice conditions.



Many observations of the Onega bay were provided in 1970s and 1980s[1,2,3]. The main features of hydrological regime were defined for the marine part of the Onega mouth area. Less attention was paid to the river part of the mouth area. Since that time, no new research was conducted.

2. Methods

Field work was carried out at the Onega River estuary by the Department of Land Hydrology (Lomonosov Moscow State University) and the Zubov State Institute of Oceanography (Roshydromet) in February and August of 2017 in order to investigate winter and summer hydrological conditions. It included measurements of water levels, velocities, discharges and salinity over a tidal cycle at locations marked on scheme(Figure 1). Water levels were measured in the mouth cross section of the estuary and cross sections of 2, 6, 13, 18 and 22 km upstream by automated water level loggers (Solinst and Keller) with measurement frequency of 5 minutes. Obtained data were used for studying tidal wave transformation. Both in summer and winter discharge measurements were performed near the hydrological station Porog using Acoustic Doppler Current Profilers (ADCP) RiverRay by Teledyne for determining the river flow without tidal influence. Velocities were measured at two cross sections (2 km and 6 km up the mouth cross section) over the one tidal cycle (approximately 12.5 hours) synchronously. In August velocity and discharge measurements were carried out by ADCP, in February observations on multiple vertical profiles were done using propeller current meters (ISP-1M and Valeport Model 106). Winter discharges were measured at 6 km. Along with velocities, salinity and temperature were measured using multiparameter sondes (YSI 600 and YSI 6000). Also ice rails and drill were used to determine features of ice cover.

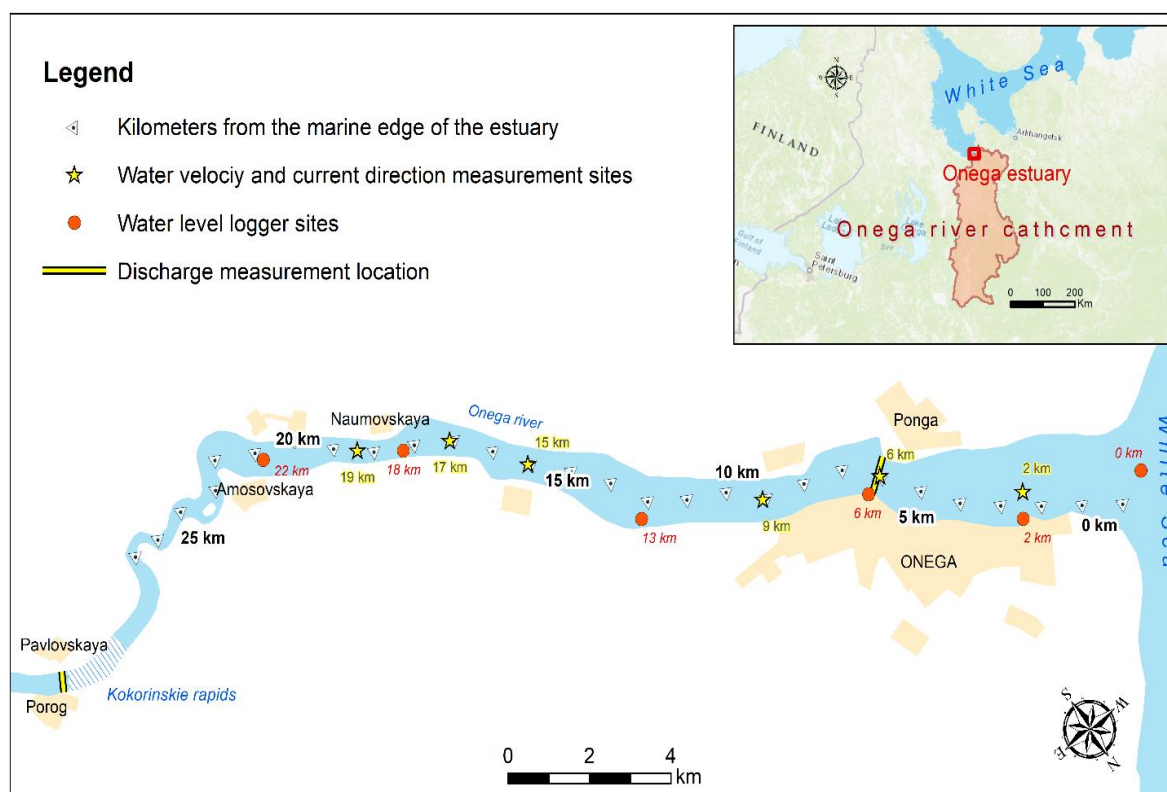


Figure 1. The Onega estuary scheme (with arctic map box) and observation sights (level, salinity, velocity, discharge).

3. Results

3.1. Winter hydrodynamic conditions

River discharge, measured near the Porog hydrological station, was $80 \text{ m}^3/\text{s}$, which is very low for the Onega River. This discharge describes river conditions without tidal influence.

Measured ice cover thickness was about 50 cm. Ice cover was not homogeneous and consisted of genetically different layers: upper layer was snow ice, bottom layer was crystal. At the upper estuary there was a third sludge layer. Ice ridges up to 1.5 m height were formed everywhere over the 20 km of the estuary mostly along the banks. Fairway was mostly covered with flat homogeneous ice.

During winter measurements there was a strong wind surge, which affected hydrodynamic characteristics of the entire Onega estuary.

Observed tidal range at the mouth was equal 1.6 m during periods without wind and 2.1 m during wind and it stayed the same at 2 km and 6 km distance up the mouth. Significant decrease of tidal range to 1 m and 1.5 m (during wind surge) was observed between 6 km and 13 km. At 18 km water level variation was only 0.3 m and 0.7 m, and at 22 km distance from the mouth tidal oscillations faded out entirely.

Average flow velocities, measured at vertical station, varied from -0.46 m/s to 0.42 m/s and from -0.44 m/s to 0.29 m/s at the 2 km and 6 km stations respectively (negative values describe reverse currents when water flows upstream) (fig.2). Maximum of flood velocity was observed about 1 hour before high tide at 6 km and simultaneously with max water level at 2 km. Vertical velocity distribution was significantly influenced by ice cover. Peak flood (negative) velocities are located closer to the bottom than maximum ebb (positive) velocities (fig.3). Flow direction changes was first observed near the bottom and closer to the banks and then in the main part of the channel (fig.4). Discharges varied from $-1015 \text{ m}^3/\text{s}$ to $750 \text{ m}^3/\text{s}$ at 6 km from the mouth. Average river discharge over tidal cycle was $80 \text{ m}^3/\text{s}$, which is close to the value, measured at the Porog. Distance of reverse currents propagation was about 18 km, during wind surge negative values were obtained at 19 km.

Distance of salt water intrusion (1 psu value) was about 2,5 – 3 km and 4 km up the mouth without and with wind surge respectively. During tidal cycle, values of mean salinity varied from 0.15 to 1.25 psu during calm conditions and 0.16-4.66 psu during wind surge thus there was more intensive salt intrusion because of wind. Salinity maximum was observed 30-50 minutes after high tide. The highest value was measured near the bottom, during wind surge it was 5.69 psu while near the surface salinity was only 2.43 psu. Vertical salinity gradient was most notable during first hours after high tide.

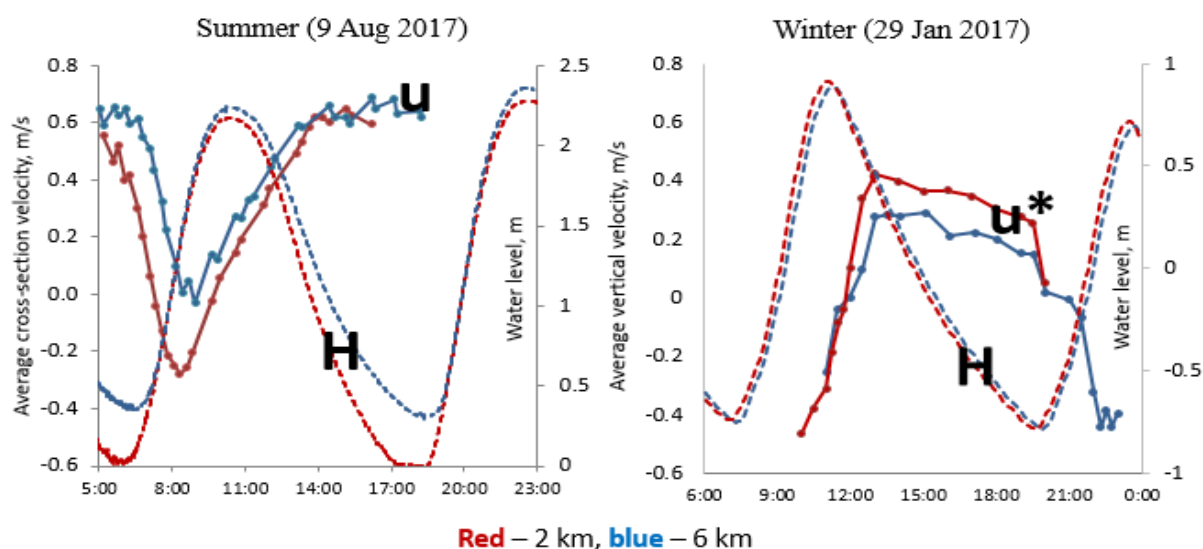


Figure 2. Average velocities and water levels during tidal cycle at 2 km and 6 km.

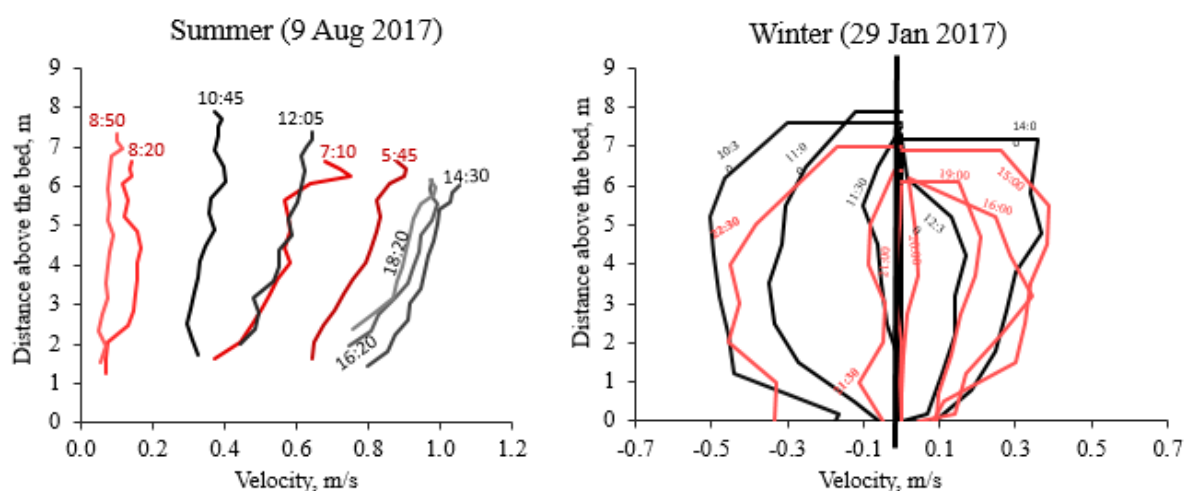


Figure 3. Flow velocity profile variation over a tidal cycle during the summer and the winter field campaign.

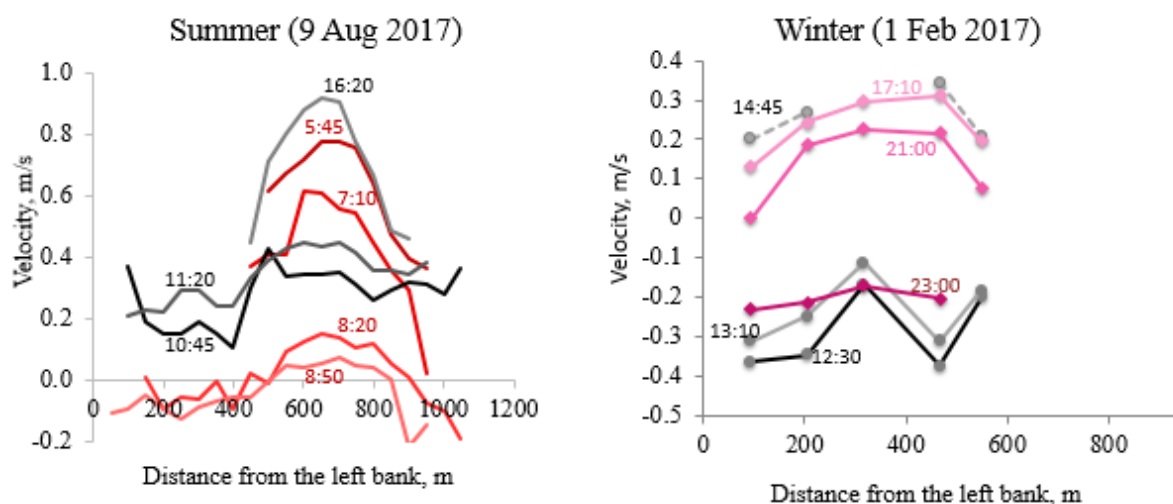


Figure 4. Variation of the depth-average flow velocity distribution at the 6 km cross-section over a tidal cycle.

3.2. Summer hydrodynamic conditions

River discharge near the Porog station was $1250 \text{ m}^3/\text{s}$ while typical discharge during summer low water is about $200 \text{ m}^3/\text{s}$. In this way, an unusual picture of interaction between the river and the sea waters in the Onega estuary were observed during the summer period.

Tidal range was about 2.3 m at 2 km and 2 m at 6 km. It decreased to 0.7 m at the 12 km and tidal oscillations almost faded out at 18 km (observed tidal range was about 0.15 m). At 22 km water level variation was about 0.07 m. Thus, the picture of water level oscillations in August of 2017 was similar to what was observed in February during wind surge.

Average cross section velocities, calculated from discharges, varied from -0.28 m/s to 0.65 m/s and from -0.03 m/s to 0.69 m/s at the 2 km and 6 km stations respectively (fig.2). Maximum tidal discharges were $-1367 \text{ m}^3/\text{s}$ at 2 km and $-109 \text{ m}^3/\text{s}$ at 6 km. Negative discharge and velocities were measured only once, so duration of reverse currents was less than 30 minutes. Maximum ebb discharges were $2791 \text{ m}^3/\text{s}$ and $1987 \text{ m}^3/\text{s}$ at 2 km and 6 km stations respectively. Thus, in August

propagation distance of reverse currents was significantly less than in February. Maximum flood velocity was measured about 50 min before the high tide at 6 km and about 1.5 hour before the high tide - at 2 km. The peak of negative velocities and discharges occurred simultaneously at both cross-sections in contrast with the peak flow during ebb (maximums positive discharges were observed earlier than velocities). From the velocities, measured the station on the fairway at 6 km, it can be seen that there were no negative velocities observed during tidal cycle. But, as it was stated above, there were changes of flow direction over the entire cross-section for a very short period of time (less than 30 min) (fig.3). Cross-section velocity measurements show that reverse currents occurred closer to banks, while at the fairway river flow obstructed tidal propagation (fig.4). When negative discharge was observed, velocities on the fairway were about 0.03-0.08 m/s through the depth, but there were strong negative velocities (from -0.05 m/s to -0.12 m/s) near the left bank for 500 m width and also small zone near the right bank. Maximum of flow velocity on the fairway during ebb located near surface and was about 0.9 m/s. At the beginning of tidal influence flow velocities decreased quickly except surface layer and large velocity gradient was formed. After an hour vertical distribution became homogeneous (0.07-0.12 m/s) through the depth (fig.3).

Salt water did not propagate into the estuary due to large river flow, while usually during summer low flow period distance of salt intrusion (1 psu) is about 6-10 km [3].

3.3. The Onega River estuary zoning

As a result of winter field data analyses the Onega River estuary zoning is presented (fig. 5). The distance of salinity intrusion was 3,2 km from the mouth cross section, reversed currents propagation was 17,5 km and propagation of tidal water oscillation was 22 km.

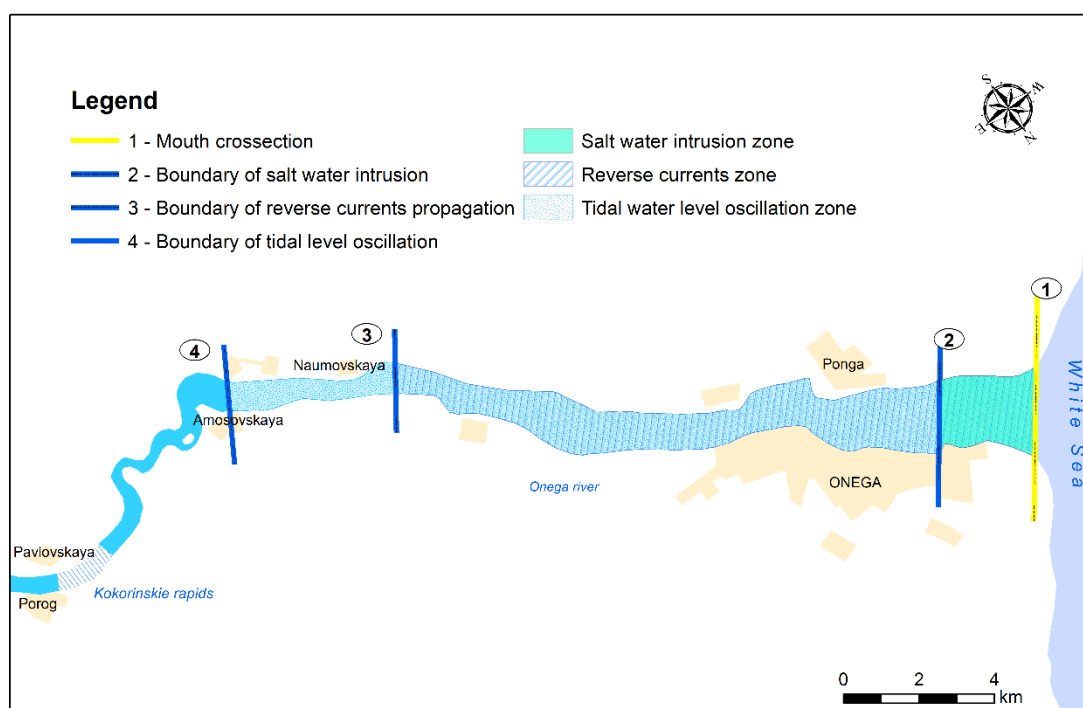


Figure 5. Winter zoning of the Onega River estuary.

4. Discussion

The concept of river mouth area as a special geographical object has been developed in Russian hydrology since 1950s [4,5]. However, today there are still no special water use rules for estuarine

areas and no methodologies for developing standards of acceptable water use limits, such as maximum permissible concentrations and others. They are determined only for rivers and sea, while in most cases the border between the river and the sea cannot be established certainly and reasonably.

The observations were made at the Onega River mouth show how changeable flow dynamics can be in a tidal estuary. For the most part of the year, reverse currents appear for a period of 4 to 5 hours during flood. The magnitude of these currents varies depending on river flow and tidal range and wind conditions.

So, when designing water intakes and spillways within the mouth area or organising water quality monitoring, it is necessary to provide comprehensive field observations. Observations can be standardized and carried out for two or three different hydrological situations. The remaining range and critical variants can be simulated using hydrodynamic model.

Today there are many software systems for modelling hydrodynamics in natural water bodies. All of them are based on the Navier-Stokes equations and advection-diffusion equations or their modifications. However, the most important element in building a computer model of flow dynamics in natural water object should be the use of field data. At the same time, monitoring and expeditionary observations should be provided according to a special program for creating a model.

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