BORE AT SHALLOW MACROTIDAL ESTUARY OF MEZEN RIVER

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Introduction

Tidal bore is a surge propagating upstream a river mouth during the rise of tidal water level. The small depths of river mouth and the funnel like shape of estuary increase the range of water level variations, especially, when river runoff is low. The water entering the funnel like, shallow river mouth rapidly moves upstream the river as a steep wave with velocity of up to ~12 m/s. The first wave is commonly followed by several waves with lower height that is called an undular bore. The bore may disappear in wider and deeper parts of river channel and reappear in narrower and shallower parts further upstream. The occurrence of tidal bore depends on four main factors: tidal range, river flow, bottom friction and funnel shape of estuary.

Mezen River estuary. The Mezen River falls into Mezenskiy Bay of the White Sea, forming the estuary of classical funnel-shape. The mouth cross section of the estuary is the section line between capes Masliany and Riabinov (Figure 1), and its head is located at 40 km from the mouth near the city Mezen. The estuary of Mezen is a macro tidal one, where the mean tidal range *h* at the mouth cross-section equals to 7.8 m, and maximum spring *h* reaches ~ 9.8 m [*Demidenko*, 2012]. Ebb-flood asymmetry of the tidal wave at cross-section Kamenka becomes 10 (9) h and 2.5 (3.5) h during spring and neap tide correspondingly. Average discharge *Q* at the mouth of the river is ~ 868 m^3/s.

Coefficient Chezy C [$m^{0.5}/s$] was calculated with the help of the formula – $u = C\sqrt{RI}$, where u – is the mean velocity of the flow in estuary [m/s], R – is the hydraulic radius [m] (~ water depth for shallow flow), I – is the bottom slope. Maximum value of Chezy coefficient at the mouth cross-section varies in the range 55 – 58 $m^{0.5}s^{-1}$, depending on the water level, and gradually decreases in the landscape direction, the minimum value at the head of estuary – C = 38 $m^{0.5}/s$ [*Dolgopolova, Mishin*, 2015]. The dimensionless Darcy-Weisbach coefficient f can be estimated by $f = 8g/C^2$, where g = is gravitational acceleration. For different sites of the Mezen estuary f changes in the range 0.02÷0.04, the largest magnitude corresponds to the reach between Okulovsk and Mezen.

Decrease of width B and depth H in the landscape direction of the Mezen estuary can be described by exponents with the power $\beta=1/L_B$ – width convergence coefficient and $\gamma=1/L_H$ – depth convergence coefficient, L_B, L_H are convergence width and depth length scales correspondingly. For the most estuaries L_B is of order of 10 – 50 km, and L_H is much larger than L_B because the depth is very weakly decreasing in landscape direction. The decrease of width of the Mezen estuary is described by β=0.054 1/km and L_B ~ 18.6 km. New data on the decrease of the depth and cross-sectional area along the estuary up to the city Mezen enable us to estimate depth convergence coefficient as γ=0.02 1/km and $L_H \cong$ 45 km. For the Mezen estuary one can not consider γ<< β and use the linearized analytical solution for description of the tidal wave evolution along the estuary.

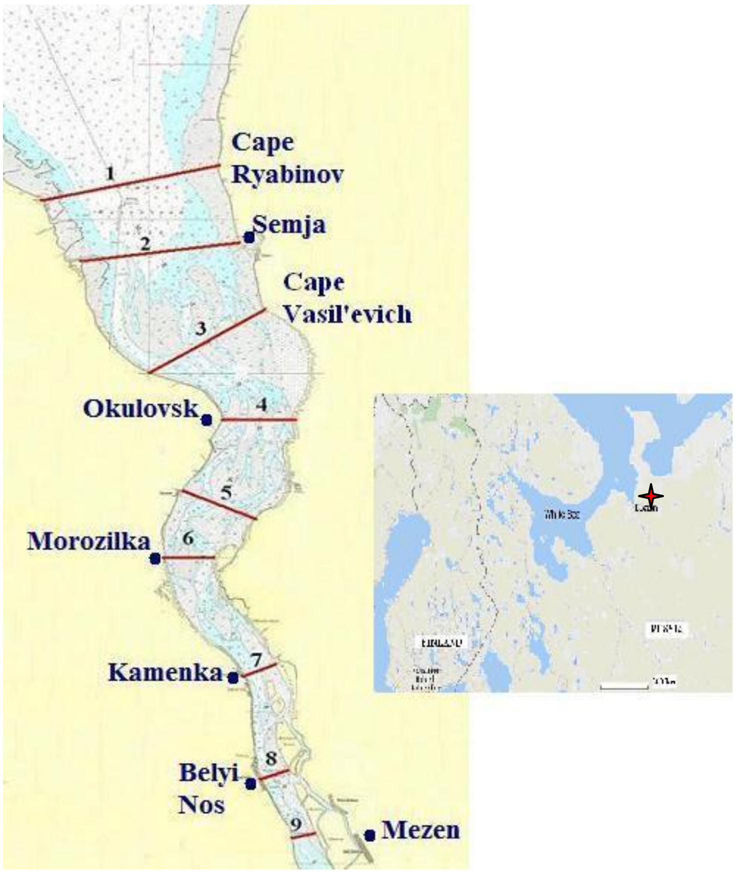

Figure 1. Scheme of the Mezen River mouth.

Estuary circulation and sediment motion at the Mezen estuary. One of the main characteristics of river mouth is the ratio of volumes of fresh *W* and salt *P* waters brought to the estuary due to river discharge and flood tide. The ratio $W/P \cong 0.01$ indicates the Mezen estuary as a partially mixed one with weak stratification. The length of intrusion of brackish water into the estuary ranges from 10 to 36 km (settlement Kamenka) from the mouth cross-section depending on the tidal phase and *Q*.

At a tidal river mouth estuarine circulation strongly impacts sediment motion. Bottom current of brackish water, moving upstream during flood, carries sediment to the point of its zero velocity (to the boundary of salt water intrusion), forming turbidity maximum zone (TMZ) in a close vicinity of this point. The upper layer of fresh river water moves to the sea. At macrotidal shallow estuary the structure of the flow is quite different: the water body of such estuary is practically well mixed; at flood unstratified flow of large velocity (~ 2 m/s and more) moves upstream, occupying the whole cross section of the estuary, at the ebb the whole flow moves to the sea. However, at the boundary of brackish water intrusion into the macrotidal shallow estuary TMZ is also formed.

The width of the silted flat area along the Mezen estuary banks varies in the range 250 – 500 m. Spring tides are the periods of accretion of these flats. In summer the rate of morphological evolution is high and bottom topography is changeable. In the cross section Semja (6 km from the estuary mouth) maximum concentration *C* of sediment in the bottom water layer reaches 0.9 and 13 kg/m^3 during neap and spring tide correspondingly [*Polonskii*, 1992]. The TMZ is formed at the reach 32 – 36 km from the mouth (settlement Kamenka), where in the bottom layer $C = 1.7 \div 2.0$ kg/m^3.

Ice dam annually forms at the cross-section 5 (Figure 1) at the distance of ~ 20 km from the Mezen estuary mouth. Downstream this dam there is no stable ice through the winter. Ice crust covering flats and laidas blocks influx of fine sand and silt into water. As a result in winter mean *C* in TMZ is smaller than that in summer by the factor ~ 100. The backup upstream the ice dam diminishes flow velocity of ice covered flow to u ~ 0.2 m/s, that is too small for sediment transport [*Polonskii*, 1992, *Demidenko*, 2012].

Criterion of tidal bore formation. Wave of bore can be described as a hydraulic jump in translation with the help of the Saint-Venant equations. The Froude number Fr_b for bore moving with the velocity *V* equals to [*Reungoat et al.,* 2012]:

$$Fr_b = \frac{U+V}{\sqrt{g \cdot A/B}} \tag{1}$$

where *U* is the river flow velocity and *A*/*B* = *H* is the depth of the flow upstream the bore averaged over cross-section, A is the cross-sectional area.

Bore exists when $\mathrm{Fr}_b>1$. The type of the tidal bore (undular or breaking bores) depends on its Froude number: at $1<\mathrm{Fr}_b<1.8$ an undular tidal bore is observed and at $\mathrm{Fr}_b>1.8$ the bore becomes a breaking one [*Chanson*, 2009].

For the river flow the depth averaged coefficient of vertical diffusion $\overline{K_y}$ equals to $\overline{K_y}$ $=0.066\cdot\kappa\cdot n\cdot\langle u\rangle H$ [*Dolgopolova,* 2013], where κ is the Karman's constant, *n* is the power exponent in the power law of depth velocity distribution, $\langle u\rangle$ and *H* are the depth averaged velocity and the depth of a river flow. For the range of n typical for plane rivers of order 0.1–0.3 dimensionless coefficient $\overline{K_y}$ varies in the range $\overline{K_y}/\langle u\rangle H$ =0.0026–0.008, which is one order less than that for the bore front. Increase of $\overline{K_y}$ at the front of tidal bore enhances vertical mixing of the flow and sediment roiling at this reach. Most of suspended sediment of the TMZ in the Mezen estuary deposits at this site during the flood-ebb change, inducing shoaling of the riverbed. At an average The Mezen estuary has shallowed through last 100 years by ~ 2 m [*Demidenko*, 2012]. The ratio of H/H_0, where H_0 is the depth at the river mouth, considerably exceeds the range 0.1 – 0.4 for estuaries without bore, and is about 0.7 at the Mezen estuary. Thus, there are all conditions for bore formation in the Mezen estuary.

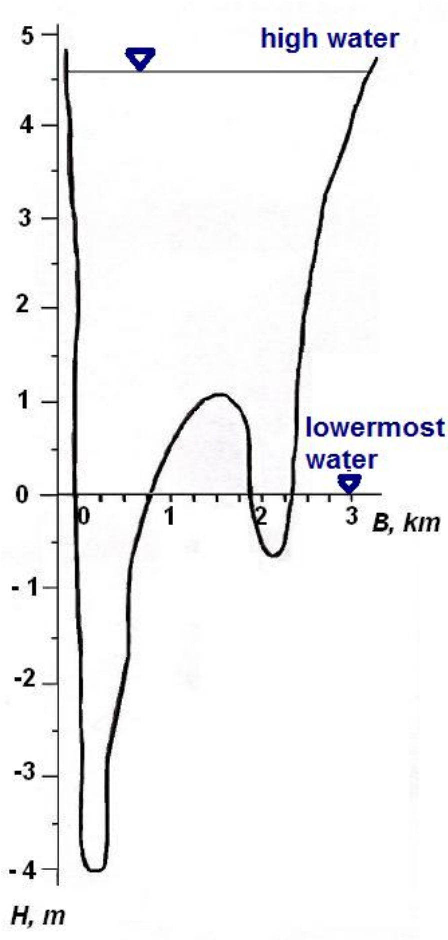

Figure 2. Tidal bore at the Mezen estuary (a) and cross section Kamenka with the Island Vanina Koshka (b).

Figure 3. View from upstream of the cross section Kamenka.

Using the magnitudes of H in (1) measured at low water we obtained $\mathrm{Fr}_b \geq 1$ for several cross-sections, in particular, for Okulovsk and Kamenka (Fr_b =1.3), where breaking tidal bore was observed (Figure 2 a). This site is also the upper limit of sea water intrusion and TMZ. In this cross-section the flow at low water consists of two currents divided by the island Vanina Koshka (Figures 2 b, 3). At comparatively moderate $\mathrm{Fr}_b \sim 1.3$ one can see in Figure 2 a the breaking bore. The same bore was observed in the shallow branch of the Garonne estuary, which was called an “atypical” bore by the authors of the paper [*Bonneton et al*, 2011].

Conclusion. Investigation of Mezen River mouth shows the existence of conditions of bore formation at the reach between settlements Okulovsk and Kamenka. Because of bottom shape evolution, the sites of bore formation are not stable and could be observed at different cross sections depending on phase of tide and river discharge.

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