ESTIMATE OF TURBULENCE ENERGY IN ICE-COVERED FLOW AND ITS INFLUENCE ON RIVER HABitat

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ABSTRACT
The energy balance of nature ice-covered flow with stable slope is investigated. The ratio of energy loss for viscous friction to the full energy of the stream and production of turbulence energy is estimated. The experimental results of turbulence impact on fish behavior in open flume are presented. Turbulence intensity in open flow is compared with that in ice-covered nature stream.

INTRODUCTION
The structure of river flow changes considerably due to damming and regulation. Alteration of riverine habitat due to dam construction operates many kilometers below the dam, usually outside the boundaries of studies intended to delineate downstream effects of dam. By detailed experiments with fish in laboratory it was shown that turbulent fluctuations of flow velocity are very important for fish movement in open stream (Skorobogatov, Pavlov and Lupandin, 1996). It is known that most of fishes spend winter in pits, but there are several species which feed and even spawn under ice-cover, such as Siberian sturgeon (Acipenser baeri Brandt), salmon (Salmo trutta L.), white salmon (Stenodus leucichthys (Güld)), sig (Coregonus) etc. Since huge amount of rivers are regulated, we meet the problem of investigation and mitigation of consequences of dams and improvement of fish habitat. The purpose of this paper is estimate of mean energy losses and turbulent energy production of ice-covered flow in regulated river in comparison with open stream and to delineate possible changes in habitat conditions in winter.

FLOWS IN REGULATED RIVERS
Due to flow regulation river discharge in winter $Q_w$ may become as large as summer one, $Q_s$. The estimate of cross-sectional area of a given river in winter, $S_w$ is less than that in summer $S_s$ at least by $\delta H_w$, where $\delta$ is the thickness of ice and $H_w$ is the depth of the flow in winter. Taking into account that most of rivers can be described as a plane flow and using $Q_w \approx Q_s$, one finds that mean velocity of the regulated river in winter $V_w$ can be larger than that in summer $V_s$ by $(\delta H_w)-100 \%$. The estimate for the River Moskva gives $V_w > V_s$ by 12.5 % ($\delta = 0.25$ m, $H_w = 2$ m).

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TRANSFORMATION OF ENERGY IN RIVER FLOW

Let us consider an ice-covered flow of the depth $h$, width $B$ and stream-wise velocity $u$ in the system of coordinates: $x$ is stream-wise axis, $y$ is vertical axis ($y = 0$ is the bottom), $z$ is transverse axis. The column of water of unit area moving in the flow of stable slope permanently loose potential energy due to lowering of its center of mass. This energy is the source term in the mean kinetic energy balance equation. One part of this energy dissipates due to viscosity and the other one goes into the production of turbulence energy. The latter is the source term in the equation for turbulence energy balance. In comparison with an open flow ice cover produces two additional sources of energy losses: (i) the second viscous sublayer, where the fraction of mean energy dissipates, (ii) mixing layer as a result of interaction of bottom and ice cover flows appears in the middle of the flow. Considering an ice-covered flow as a stream composed of two currents, which are formed by bottom and by the ice cover, we will estimate the energy losses in an ice-covered flow by the method developed for open channel (Dolgopolova, 1999).

**Losses of mean motion energy**

To evaluate the fraction of energy dissipated due to viscous friction at the boundaries of the flow, we consider thin layers in which the components of turbulence stress tensor are negligibly small. The dimensionless thickness of the layer near the bottom is $yu_*/v<5$ (Schlichting, 1969), where $u_*$ is shear velocity, $v$ is the coefficient of kinematic viscosity. The mean flow energy equation for the plane flow is

$$\text{Potential Energy } E_0 = \text{Kinetic energy} - \text{Viscous dissipation at the boundaries} - \text{Production of turbulence}$$

The energy of viscous dissipation in the unit layer of water close to the bottom may be estimated as (Svensson and Andreasson, 1989):

$$\mu \left( \frac{\partial u}{\partial y} \right)^2 = \tau \frac{\partial u}{\partial y} = \rho^2 u_*^3 / \mu ,$$

where $\mu$ is molecular viscosity, $\mu = \nu \rho$, $\tau$ is shear stress, $\rho$ is density of water. Multiplying this expression by the thickness of viscous sublayer we obtain the magnitude of energy $E_v$ lost due to viscosity

$$E_v = 5 \rho u_*^3 .$$

Using Eq. 1 for assessment of energy dissipated in viscous sublayers near bottom $E_{vb}$ and near ice cover $E_{vi}$ we obtain for viscous dissipation in ice-covered flow

$$E_v = E_{vb} + E_{vi} = 5 \rho (u_{vb}^3 + u_{vi}^3) .$$

Introducing the depth averaged velocity $<u>$, we evaluate the significance of this term with the net input of energy

$$E_0 = <u > (\tau_b + \tau_i) .$$

Using Eqs. 2 and 3 and taking into account the expression $u_* = \kappa n <u>$ (Dolgopolova, 1998), we obtain

$$\frac{E_v}{E_0} = \frac{5 (u_{vb}^3 + u_{vi}^3)}{(u_{vb}^2 + u_{vb}^2) <u>} .$$
The ratio $E_v/E_o \approx 0.3–0.35$ for open streams obtained by Dolgopolova (1999) is in good correspondence with that found by numerical calculation by Svensson and Andreasson (1989).

For the River Moskva in winter we have mean value of $E_v/E_o = 0.36, 0.37, 0.38$ for cross-sections I, IV and V correspondingly (Table 1, details of experiment see in paper by Dolgopolova, 1998). There was a warm water discharge at the cross-section II, so the estimate of the ratio (4) for cross-sections II and III is not reliable. Comparison of the viscous energy losses for open ($E_v/E_o = 0.34$ for cross-section I) and ice-covered (cross-sections I, IV, V) flows in the River Moskva shows the increase of these losses by $\sim 10\%$.

**Equation for energy of turbulence**

Let us consider Reynolds equation of turbulence energy balance in approximation of plane flow as:

$$K + D_2 - S + D_1 + T = 0, \quad (5)$$

where $K$ is the amount of energy which is transported by averaged motion inside the elementary volume during the unit of time; $D_1$ is the term describing fluctuating energy diffusion, $D_2$ is the work of pressure fluctuations, $S$ and $T$ is the transformation of the mean motion energy due to viscous dissipation and into the energy of turbulent fluctuations correspondingly. The last term in Eq. 5 equals to

$$T = -\frac{\partial u}{\partial x} u'^2 \left( \frac{\partial u}{\partial y} + \frac{\partial w}{\partial x} \right) u'w' - \frac{\partial w}{\partial y} w'^2, \quad (6)$$

where local time averaged velocity is $u_i = \bar{u}_i + u'_i$, the indices $i = 1, 2, 3$ are in correspondence with the axes $x, y, z$, and components of velocity $u, v, w$.

**Production of turbulence energy**

To estimate the magnitude of turbulence energy production in plane river flow one can use the expression

$$T = -u' v' \frac{\partial u}{\partial y}. \quad (7)$$

Using linear relationship for turbulence stress distribution through the depth, power law for mean velocity profile and normalizing $T$ to $h/\langle u \rangle^3$, one obtains for dimensionless production of turbulence energy $T'$ in open channel

$$T' = \kappa^2 n^3 (1 + n)(1 - y/h) \left( y/h \right)^{n-1}. \quad (8)$$

The depth distributions of $T'$ for open flows in different rivers in summer, which are shown in Fig. 1 are in good agreement with distributions calculated by Eq. 8 for the power exponent range $0.1–0.3$ (the latter is valid for rivers of bottom roughness comparable to depth). For this range of $n$ calculated values of depth averaged turbulent energy $\langle T' \rangle$ for open river flows equal to $0.0016 – 0.0144$. Using Eq. 8 and data on the flow in the River Moskva (Dolgopolova and Tesaker, 2000) we evaluated the total energy for given vertical position as $\langle T'_0 \rangle = \langle T'_b \rangle + \langle T'_i \rangle$ and then turbulent energy production averaged across the Moskva River $\langle T'_0 \rangle$ (Table 1).
The magnitudes of $<\bar{T}_0>$ in cross-sections I, IV and V are the typical values for ice-covered flow, while II and III are affected by warm water discharge.

Table 1: Data of experiment in the River Moskva in winter

<table>
<thead>
<tr>
<th>Section, Section</th>
<th>$B$, m</th>
<th>$x$, m</th>
<th>$&lt;u&gt;$, m/s</th>
<th>$u$, m/s</th>
<th>$&lt;\bar{T}_0&gt;$</th>
<th>$&lt;u&gt;_i$/ $&lt;u&gt;_s$</th>
<th>$&lt;\sigma&gt;_i$/ $&lt;\sigma&gt;_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, 64.8</td>
<td>0</td>
<td>0.41–0.53</td>
<td>0.40–0.50</td>
<td>0.0126</td>
<td>1.30</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td>II, 56.6</td>
<td>80</td>
<td>0.36–0.49</td>
<td>0.28–0.55</td>
<td>0.0605</td>
<td>1.35</td>
<td>1.81</td>
<td></td>
</tr>
<tr>
<td>III, 52.7</td>
<td>120</td>
<td>0.38–0.49</td>
<td>0.34–0.48</td>
<td>0.0293</td>
<td>1.31</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>IV, 64.1</td>
<td>740</td>
<td>0.31–0.50</td>
<td>0.28–0.51</td>
<td>0.0113</td>
<td>1.60</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>V, 71.1</td>
<td>820</td>
<td>0.28–0.31</td>
<td>0.20–0.37</td>
<td>0.0134</td>
<td>1.30</td>
<td>1.82</td>
<td></td>
</tr>
</tbody>
</table>

Legend: $u =$ flow velocity at $y = 0.17 \div 0.29$, $<u>_i$/ $<u>_s$, $<\sigma>_i$/ $<\sigma>_s =$ ratios of the largest depth averaged magnitude to the smallest one in given cross-section.

EXPERIMENTS WITH FISHES IN FLUMES

Orientation of fish in space is realized by different mechanisms, one of which is moving against the stream. There are several quantitative characteristics of this movement among them are critical velocity of the flow (the velocity of the flow, to which fishes can not resist) and buoyancy of fish, which can be measured as time period during which fish can resist the stream of definite mean velocity.

Critical velocity of the flow and influence of turbulence intensity on fish movement were performed with roach youth (*Rutilus rutilus* L.) of mean length 24.5 mm in a flume (length = 1.5 m, width = 0.1 m), upper and lower ends being limited by nets (Pavlov, Skorobogatov and Shtaf, 1982). Fishes adapted at the lower end of the flume for ~10 min, then velocity was gradually increased and the place of fish drift was marked. Velocity of the flow was registered at this point for 50 s, as a result critical velocity $V_c$ and turbulent intensity of the flow $K = \sigma / V_c$ were obtained. Experimental results presented in Fig. 2 show that the increase of $\sigma$ by 40 % results in decrease of $V_c$ by 40 – 50 %.

Investigation of velocities and turbulence intensity preferable for roach youth was carried out in flume (length = 2.0 m, width = 0.4 m), the width of which was separated into 4 sections of 0.1 m each (Skorobogatov et al., 1996). Velocity and turbulence intensity of the flow changed in ranges $u = 0.077 \div 0.095$ m/s ($u/u_s = 1.4 \div 2.0$) and $\sigma = 0.0087 \div 0.0242$ m/s ($\sigma/\sigma_s = 1.2 \div 2.8$) correspondingly. The analysis of results of measurements shows that fishes are sensible to difference between $\sigma$ and $\sigma_s$ in case it exceeds 40 %. In cases $u/u_s = 1.4$ and $u/u_s = 2$ fishes preferred the sections with larger turbulence intensity up to $\sigma/\sigma_s = 2$. When $\sigma/\sigma_s > 2.1$ fishes chose more quiet areas.

Investigation of buoyancy of different species of sturgeon (*Acipenseridae*) at the early period of development was carried out in flume flow of mean velocities 0.158 and 0.2 m/s and depth 0.2 m (Khodorevskaya, 1979). The results of the experiment show the increase of buoyancy with young fish length growth during first months of their life before the freezing-up up to 5 minutes for beluga (*Huso huso* L.) and sturgeon (*Acipenser güldenstädti Brand*) and 33 minutes for sevruga (*Acipenser stelatus Pallas*)
at flow velocity 0.2 m/s. Information on buoyancy of fish juveniles enables one to assess velocity characteristics of fish habitat in winter.

CONCLUSIONS

To compare energy of turbulence in ice-covered flow with that realized in experiments with fishes in flumes, we calculated \( \sigma_u / <u> = \sqrt{2T'} \) at the level of 0.2–0.3 m from the bottom varying in the range 0.06–0.16, that is about 2 times larger than these magnitudes used in experiments with fishes in flume (Fig. 2: 0.03–0.08). Comparison of turbulence intensity at \( y = 0.2 \) m for open (Grinvald and Nikora, 1988) and ice-covered rivers shows that \( \sigma_u / <u> \) measured in ice-covered flow exceeds that in open channel by factor 2.

Comparison of distribution of \( <u> \) and \( <\sigma> \) across the ice-covered flow (Table 1) with those realized in experiments with fishes shows, that at all values of \( <u> / <u>_s \) fish would choose places with maximum turbulence intensity. It is difficult to analyze fish behavior, because velocities in ice-covered flow in the River Moskva at \( y = 0.2–0.3 \) m are considerably larger than those in flumes. Increase of the mean velocity of the flow in winter mentioned above may be less than 12.5 % \( V_s \) since additional part of energy is converted into turbulent energy in ice-covered flow. Mean velocities of the flow of the River Moskva at horizons \( y = 0.2–0.3 \) m in the cross-section I in summer are \( u = 0.30–0.35 \) m that is larger than velocities in ice-covered flow \( u = 0.20–0.55 \) (Table 1), the difference between summer and winter velocity depending on the regime of power station.

Mean velocity and turbulent intensity in regulated river at the depth where youth lives are larger than those in open flows and those realized in experiments with fishes in flumes. So evidently, ice-covered flow in regulated river can move spawn and fry to unsuitable places for incubation and feed.
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REFERENCES