Turbulent Structure of Ice-Covered Flow and Ice Impact upon Habitat in Rivers

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Provisional estimate of the influence of stable ice cover at the surface of river on the habitat conditions in the bulk of the stream and near the bottom are presented. The change of the flow structure under winter conditions is described in terms of mean the velocity and fluctuations of longitudinal component of velocity of the river. The results of measurements in rivers under both free surface and ice conditions are compared.

1. Introduction

Investigations of fresh water quality show negative influence of human activity on water quality of rivers and lakes. Although much efforts are spent to work out new closed-circuit technologies till now rivers remain collectors of waste waters. When using rivers in national economy it is important to preserve not only water quality but the ecosystem of a river as a whole. In this work we consider the changes of structure of nature streams due to ice cover and estimate its influence on habitat in rivers.

2. Basic Components of Habitat in Rivers

To estimate impact of ice cover on river ecosystem it is necessary to consider the main characteristics of habitat conditions, most important of which are related to water quality, velocity and depth of the river and composition of bottom sediment [Tesaker (1998)]. As it was noted by Shen (1998) the ice cover produce considerable effect on water quality. The important characteristic of water quality is concentration of dissolved oxygen. White (1998) has mentioned, that the occurrence of oxygen depressions in rivers under winter conditions have been attributed to lack of reaeration due to the ice cover, oxidation of organic material and inputs of oxygen-depleted groundwater. The other source of deterioration of water quality of an ice-covered river is high metal concentrations during the breakup periods [Beltaos (1998).As it will be shown below due to turbulization of the flow and river bed erosion the concentration of metals which are largely absorbed by sediment particles may increase locally under the stable ice cover.

Velocity is an important factor which is responsible for the life conditions of the invertebrate fauna inhabiting the boundary layer between the river substratum and the bulk of water. Velocity of a flow in this layer is very small; at the same time it is the main source of oxygen exchange in this layer. Investigations of different authors summarized by Gore (1989) show that the optimum magnitudes of velocity for life of the invertebrates are within the range: 0.15 ÷ 0.9 m/s.

The river depth defines an amount of light penetrating into water and taking part in photosynthesis of water plants, providing food for the invertebrates. The deeper is the river, the less amount of light penetrates to water, and, as a consequence, the less of plant food is produced.

The connection between velocity of the stream and the sediment size is well-known: the bigger is the median diameter of sediments, the higher is velocity of the flow. The data obtained by many researches show the following dependence of number of invertebrates on the dimension of sediment particles: the number of invertebrates near the bottom sequentially decreases in the row - shingle, coarse gravel, fine gravel, sand, mud [Gore (1989)].

Thus the main habitats in rivers are rapids with velocities more than the mean velocity, with the depth less than the mean depth of the river, and with the bottom sediments consisting of shingle and gravel.

3. **Ice Impact on Characteristics of the River Flow**

Morphology of the River Bed

Morphology of the river bed plays an important role in survival of larvae and fry, especially in winter. Formation of the ice cover at water surface is often connected with production of frazel and bottom ice, which occupy considerable part of the river cross-section. Sometimes an ice-covered flow transforms into several small streams, the velocities of each of them being more than that of the initial flow at the same places in summer [Majewski (1994), Brown et al. (1998)]. The velocities of these streams can exceed the critical magnitude, in which case begins erosion of the areas stable in summer. Though such phenomena often occur in rivers in winter and their influence on survival of bottom plants and fauna is considerable, the research in this field is still in its infancy.

Sediment Transport

Sediment transport is one of the sources of pollution in an ice-covered flow. Milburn & Prowse (1998) mentioned that transport and settling of fine-grained sediments plays the most important role in secondary pollution of water. The authors show that hydraulic characteristics of a flow changed by the ice-cover induce decrease of the transport capacity of the stream, which results in deposition of the fine-grained sediments.

Sediment transport in the ice-covered flows of tidal mouths of Northern rivers in Russia was investigated by Zyryanov (1995). The streams of the rivers flowing into the Arctic Ocean decline to the right. Studying the motion of the fine-grained sediments in the mouth of Western Dvina, the authors have found out experimentally and explained theoretically that suspended fraction of sediments (which has no time to settle during the period between the tide and ebb) declines to the left relative to the outflowing river jet. Under winter conditions, when velocity at the river mouth decreases, this fine-grained fraction of sediments containing all pollutants from the upstream towns will settle out in the left area of the river mouth.

Ettema & Braileanu (1998) presented the results of investigation of velocity of the sediment transport. In this paper shear velocity is estimated and the expressions for the rate of bed-load and suspended-load transport in the ice-covered flow are presented.

To estimate the bed-load discharge it is necessary to know the relation between velocities of water and solid particles. The competent velocity has a specific value for a given stream; the accuracy of its definition depends on homogeneity of the granulometrical composition of bottom sediments.

Thus, knowing the granulometrical composition of the bed-load and hydraulic characteristics of an ice-covered water flow, one can predict the areas of washout and deposition, and as a result to define the dangerous places of possible secondary pollution of water.

Mean Velocity

Ice cover formation results in modification of the river flow structure. The ice-covered flow is formed under the influence of bottom and ice roughness. If we consider the ice-covered flow consisting of two streams formed by the bottom and underneath of ice, the velocity distribution of each of them can be described by the power laws [Dolgopolova (1996)]

$$u = u_{sb} y_b^{n_b}, \quad u = u_{si} y_i^{n_i}, \tag{1}$$

where $y_b = \frac{y}{h_b}$, $y_i = \frac{h-y}{h-h_b}$, y is the vertical coordinate, h is the depth of the flow, h_b is the depth of the near-bed flow, y_b, y_i, n_b, n_i, u_{sb}, u_{si} are dimensionless distances from the boundaries, power exponents and conditional surface velocities for near-bottom and near-ice flows correspondingly. Using the power law, the parameters of the mean velocity distributions for open and ice-covered flows were calculated and presented in Tables 1, 2, 3.

Shear Stress

Near the boundaries (bottom and ice) of a turbulent ice-covered flow the shear stress τ can be described by following expression

$$\tau = u_*^2 \rho \ , \tag{2}$$

where u_* is shear velocity, ρ is fluid density.

Shear velocity can be defined by using the depth averaged velocity $<u>$ and the power exponent n in velocity distribution [Dolgopolova (1993)]

$$u_* = \kappa n < u > . \tag{3}$$

where κ is the Karman's constant.

Substituting (3) into (2) one can estimate the bottom shear stress of the flow under both summer and winter conditions as following

$$\tau = \rho\kappa^2 n^2 <u>^2 . \tag{4}$$

This expression shows that shear stress depends on the mean velocity and the shape of the mean velocity distribution along the depth. The results of calculation of the shear stress near the bottom by using (4) for a number of rivers are shown in Tables 1, 2, 3.

Turbulent Characteristics of Ice-Covered Flow

Measurements of fluctuations of the streamwise component of velocity were used to obtain depth distributions of second , third and forth statistical moments which are shown in Figure 1. The detailed description of the experiment can be found in [Dolgopolova (1994)]. The turbulence intensity σ increases when approaching to the boundaries of the flow and has the maximum at dimensionless depth 0.7. The depth-averaged intensity of turbulence is equal to 0.4 which is approximately 5 times larger then that for open channel [Orlov et al. (1985)].

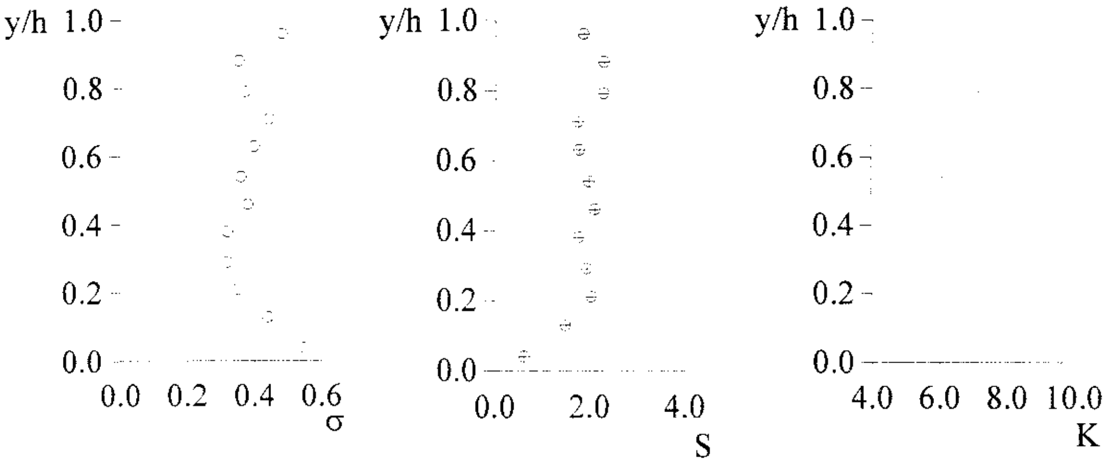

Figure 1. Depth distribution of turbulence intensity $\sigma = \sigma_u . <u>$, skewness S and kurtosis K for Moskva River in winter.

Skewness *S* and kurtosis *K* of fluctuations of the streamwise velocity in an ice-covered flow are very different from those for an open channel. Near the bottom and the ice cover coefficients of the skewness and kurtosis become close to those of the Gaussian distribution 0 and 3 correspondingly. Thus, one can expect the considerable change of the structure of an ice-covered flow as compared to the free ice conditions.

4. **Discussion**

Shear Stress

Analysis of the data in Tables 1 and 2 shows that the mean velocity of a river plays a big role in interaction between the water flow and the river bed and in formation of the bottom shear stress. The magnitudes of the power *n* obtained for the Rivers Missouri and Kirhzach depend on the depth of the river, confirming the dependence *n(Re)* found in [Dolgopolova, 1993].Cross-sectional average shear stress for the River

Missouri is more then one order greater then those for the River Kirhzach. Thus, to estimate the change of the bottom shear stress under winter conditions one needs the data of mean velocity profiles measured in the same river in summer or in the river (or flume) which scales (*B/h, Re*) are near to that under investigation.

The comparison of mean velocity profiles obtained from measurements in rivers (Tables 2 and 3) shows that the power exponent of the velocity distribution in the near-bottom flow increases under winter conditions. The mean velocities of the River Kirhzach and of the near-bottom flow of the River Moskva are numerically close, what enables us to compare the power exponents and the shear stresses for these flows. One can note considerable increase of $\overline{\tau}_b$ under winter conditions, especially at the cross-section II. where warm waste waters were discharged. Although we could not find the influence of this waste flow on the depth averaged velocity, it resulted in noticeable change of the shape of the velocity profile and hence in considerable increase of the power exponent n_b (Table 3). In conclusion, it may be said that the bottom shear stress in a river under ice increases, deteriorating the life conditions of bottom-dwelling organisms.

Turbulent Structure of Ice-Covered Flow

The depth distribution of turbulent intensity $\sigma_u = \overline{u'^2}$ of velocity fluctuations u' were investigated by many researches, for example [Sukhodolov & Tile (1999), Knight & Shiano (1990), Orlov et al.(1985)]. As a result, the intensity distribution with maximum near the bottom and decreasing to the surface of an open channel is presently accepted . The results of our investigations show that there are three maxima of the distribution of turbulent intensity in an ice-covered flow (Figure 1). Clearly, there are two of them at the solid boundaries of the flow and there is the third one at the dynamic axes of the flow $y/h \approx 0.7$, where $\tau = 0$. The fact that for plane rivers of aspect ratio $B/h >> 1$ the depth averaged turbulent intensity in ice-covered flow several times bigger than that for the open stream indicates high turbulization of the flow. The increase of turbulization of the flow and the emergence of the turbulent intensity maximum in the bulk of an ice-covered river can be explained as a result of interaction oftwo boundary layers, formed near the bottom and ice covers.

Comparing the distributions of skewness and kurtosis presented in Figure 1 with those obtained for an open channel by Dolgopolova & Orlov (1985) presented in Figure 2, one can see the discrepancy between them. If the distribution of the streamwise velocity fluctuations can be described by the first four statistic moments, then the Pearson's method of analysis can be used [Dolgopolova (1994)]. The depth averaged magnitudes $S = 2$ and $K = 6$ obtained from our measurements show, that in an ice-covered flow the fluctuations of velocity above the mean velocity occur with bigger probability then for the Gaussian distribution, and they are concentrated in a more narrow interval then for the normal law - $\pm 3\sigma$. This fact can be considered as an origin of production of coherent structures an in ice-covered flow.

Thus, the change of the flow structure and turbulization of the an ice-covered stream increase the intensity of transfer processes in river under ice cover.

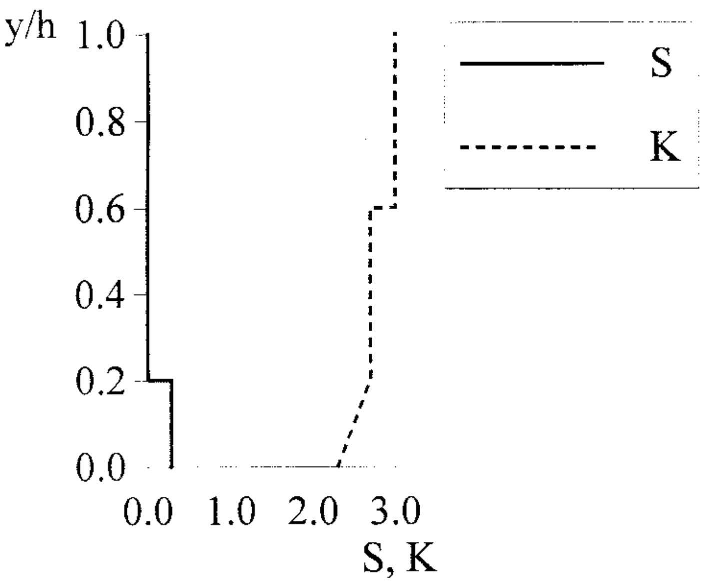

Figure 2. The scheme of division of an open stream into layers as a function of skewness S and kurtosis K.

Estimate of eddy viscosity

It is well known, that eddy viscosity ε can be estimated by mixing length hypothesis from the relationships given by Schlichting (1968). The depth distribution of the mixing length l was obtained by measurements in laboratory flume in paper [Cardoso et al. (1989)], but there are some difficulties in developing the same procedure for an ice-covered flow in nature. It seems reasonable to define ε with the help of the Lagrangian time scale of turbulence T [Fischer (1973), Fidman (1991)]

$$\varepsilon = T\overline{\left(u'\right)^2}\,, \tag{5}$$

where, $\overline{\left(u'\right)^2}$ is the variance of velocity fluctuations, $T = \int_0^\infty R(t)dt$, where $R(t)$ is the normalized correlation function of actual velocity of the same fluid particle at different moments.

The Lagrangian scale of turbulence is a measure of time during which the individual character of motion of a chosen particle is conserved. Information about the Lagrangian correlation functions is of great interest in studies of transfer processes in rivers. The Lagrangian characteristics of velocity field of the stream can be investigated with the help of visualization methods, which can be used only in laboratory flumes.

In the previous work [Dolgopolova, (1995)] we have found the relationship between the Lagrangian time scale T and the Eulerian time scale θ, which can be easily obtained from the raw data of velocity fluctuations measured in flumes as well as in rivers. On the basis of extensive studies of flows in flumes, rivers and channels performed by our laboratory and published by other authors we have defined the following connection between T and θ

$$T = \theta\, 1.4n\,. \tag{6}$$

Thus, substituting (6) into (5), one can estimate ε for both near-bottom and near-ice flows in an ice-covered stream as

$$\varepsilon=\frac{\theta}{1.4n}\sigma_u^2 \quad . \tag{7}$$

The dependence $\varepsilon=f\left(\sigma_u^2\right)$ and hence the increase of eddy viscosity in an ice-covered flow in comparison with the free-surface stream is confirmed by results of the authors developing mathematical simulations of ice-covered flow [Shen & Harden (1978)], but now we lack sufficient data for the Moskva River to verify relation (7).

5. **Conclusion**

The problem of effect of the ice cover on the habitat conditions in rivers is in the initial stage of studying. Considerable distinction between the structures of ice-covered and free surface flows and increase of the bottom shear stress in winter mentioned above seems to deteriorate life conditions in rivers under ice cover. The problem of monitoring and control of ice related habitat conditions demands further experimental research.

6. **Acknowledgments**

I would like to thank Einar Tesaker for fruitful discussion. This work was partially supported by RFBR grant No.97-05-65528.

Table 1. Calculation of the power coefficient n and the bottom shear stress for the River Missouri [McQuivey (1973)]

Number of vertical	z, m	h, m	Bottom character	n	$<u>$ m/s	u_* m/s	τ kg/m $\cdot s^2$
1	176.8	4.4	dunes	0.105	1.29	0.054	2.91
2	164.6	4.97	flat	0.194	1.84	0.142	10.13
3	155.5	4.75	dunes	0.143	1.77	0.101	10.18
4	146.6	4.36	flat	0.141	2.08	0.119	14.14
5	134.1	4.15	dunes	0.113	1.93	0.087	7.56
6	113.7	3.44	dunes	0.126	1.83	0.092	8.45
7	103.6	3.29	flat	0.155	1.88	0.117	13.66
8	68.9	1.95	dunes	0.084	1.51	0.051	2.60
Mean cross-sectional shear stress for the River Missouri is $\bar{\tau} = 9.04\, kg \cdot m / s^2$							

Table 2. Calculation of the power coefficient n and bottom the shear stress for the River Kirhzach

Cross-section	No. Vert.	z, m	h, m	n	$<u>$ m/s	u_s	u_* m/s	τ kg/m $\cdot s^2$	τ kg/m $\cdot s^2$
I B=18.5 m	1	6.0	0.47	0.185	0.37	0.230	0.027	0.728	0.342
	2	9.5	0.40	0.221	0.36	0.235	0.032	1.023	
	3	14.0	0.42	0.120	0.36	0.204	0.017	0.289	
II B=17.5 m	1	4.0	0.52	0.183	0.35	0.207	0.026	0.675	0.440
	2	7.5	0.43	0.167	0.35	0.210	0.023	0.528	
	3	11.0	0.37	0.190	0.37	0.238	0.028	0.783	
	4	14.5	0.42	0.311	0.35	0.254	0.044	1.933	
III B=17.3 m	1	4.0	0.55	0.233	0.37	0.253	0.035	1.223	0.259
	2	8.0	0.40	0.088	0.38	0.215	0.013	0.169	
	3	11.0	0.39	0.084	0.36	0.185	0.012	0.144	
	4	13.5	0.38	0.122	0.38	0.233	0.019	0.361	
IV B=16.5 m	1	3.0	0.56	0.200	0.36	0.236	0.029	0.840	0.783
	2	6.0	0.44	0.148	0.39	0.245	0.023	0.528	
	3	9.3	0.43	0.306	0.34	0.238	0.042	1.762	
	4	12.3	0.45	0.350	0.31	0.214	0.043	1.846	
	5	14.5	0.39	0.231	0.29	0.139	0.027	0.728	

Table 3. Calculation of the shear stress for the Moskva River in winter

B, m	No. Vert.	z, m	h, m	h_b m	n_b	$<u>_b$ m/s	u_{*b} m/s	τ_b kg/m $\cdot s^2$	τ kg/m $\cdot s^2$
I B=64.8	1	9.6	1.68	0.77	0.266	0.40	0.043	1.81	1.403
	2	18.8	1.50	0.80	0.263	0.47	0.049	2.44	
	3	31.8	1.55	0.64	0.231	0.45	0.042	1.73	
	4	42.4	1.72	0.81	0.199	0.52	0.041	1.71	
	5	53.6	1.73	0.69	0.160	0.41	0.026	0.69	
II B=56.6	1	9.0	1.47	0.65	0.335	0.39	0.052	2.73	6.66
	2	17.6	1.79	1.00	0.614	0.34	0.084	6.96	
	3	27.6	1.82	1.04	0.698	0.41	0.114	13.09	
	4	37.6	2.0	0.80	0.230	0.45	0.041	1.71	
	5	45.5	1.58	0.75	0.612	0.50	0.122	14.96	
III B=52.7	1	8.0	1.47	0.59	0.451	0.35	0.063	3.98	2.66
	2	16.8	1.73	0.88	0.302	0.38	0.046	2.10	
	3	26.0	1.99	0.77	0.306	0.38	0.047	2.16	
	4	34.0	2.10	0.93	0.361	0.47	0.068	4.60	
	5	42.0	2.03	0.98	0.289	0.51	0.059	3.47	
IV B=64.1	1	11.6	1.56	0.75	0.225	0.48	0.043	1.85	1.86
	2	23.0	1.55	0.78	0.230	0.46	0.042	1.76	
	3	35.0	1.79	1.10	0.289	0.44	0.051	2.60	
	4	46.4	1.58	1.00	0.256	0.40	0.041	1.68	
	5	58.4	1.66	1.00	0.237	0.30	0.028	0.78	
V B=71.1	1	20.0	1.25			0.24			
	2	28.0	1.30	0.69	0.435	0.25	0.044	1.89	
	3	37.2	1.34	0.74	0.207	0.21	0.017	0.30	
	4	54.0	1.51		0.089	0.33	0.012	0.14	
	5	67.6	1.62		0.216	0.32	0.028	0.76	

Legend for the Tables 1, 2, 3: B is the width of the river, z is the distance from the left bank, h is the depth, n is the power coefficient in the velocity distribution, u_* is the shear velocity, τ is the bottom shear stress $\bar{\tau}$ is the mean cross-sectional shear stress, subscript b is used for characteristics of the flow formed by the bottom of ice-covered stream.

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