Assessment methodology for the backwater levels caused by ice jams: a case study of the rivers of Tom and Chulym (the Ob River drainage basin, Western Siberia, Russia)

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Abstract. The article presents an assessment methodology for backwater levels caused by break-up or freeze-up ice jams. Ice jam induced backwater effects reflect changes in water and ice balance in a stream reach. The balance, in turn, depends on the ratio of thermal and dynamic factors of ice events formation. The methodology based on a scheme of jammed river longitudinal profile has been proposed and tested using the observation data on the rivers of Tom and Chulym, and it has been shown that the accuracy of assessment is around 2–12% of the measured values.

1. Introduction

High probability of floods induced by freeze-up and break-up ice jams[1] is common for many northern rivers. As a result, river valleys economic use is limited enough [1]. Main factors causing ice jams are [3]:

- decreasing riverbed slope in the transition area from highlands to lowlands and consequently decreasing river flow energy;
- earlier ice cover break-up in the upper course of rivers that flow from the south to the north in the case while continuous ice cover occurs in the lower course;
- heavy rains during the periods of ice cover freeze-up and break-up, causing deviations from normal conditions;
- presence of natural and anthropogenic river channel contractions in the lowland course of a large river where ice material accumulates.

Therefore, there is a need for developing hydrological prediction techniques that allow preventing negative ice jams consequences [5–9]. In particular, techniques allowing forecasting the dates of ice jam formation and magnitude of backwater levels induced by those jams, both under natural conditions and resulting due to anthropogenic modifications of a river channel are needed.

The most widespread in the backwater prediction practice are methods based on exploration of the river flow movement patterns [10], as well as methods based on calculations of water mass or ice cover heat exchange with the environment [13]. In the frame of those methods a number of techniques have been proposed.

At the State Hydrological Institute (SHI) of the RosHydromet, the technique for prediction of the backwater level above the water level corresponding to the multi-year average 30-days water

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[1] Hereinafter referred to as "ice jams"

discharge has been developed [19]. The technique is based on the hydraulic similarity requirements for ice jams formation process in rivers (1), (2):

$$Z_{JD,Q} - Z_{Q,wa} = \frac{Z_{Q,a} - Z_{Q,wa}}{1-\eta}, \tag{1}$$

$$\eta = 0.30 + 0.21 \cdot Fr_{Q,sa}^{0.5} \cdot A^{0.17} + 0.25 \cdot \lg\left(\frac{S_{Q,wa}}{8.5 \cdot Fr_{Q,sa}^{1.16}}\right), \tag{2}$$

where $Z_{Q,a}$ and $Z_{Q,wa}$ are the water levels under open channel conditions corresponding to the multi-year average water discharge during ice jam and to the multi-year average minimum 30-days water discharge in winter, respectively; η is the parameter characterizing relative river channel contraction during ice jam and specified as a function of the river basin area A and the Froude number $Fr_{Q,sa}$ corresponding to the multi-year average maximum water discharge in the spring flood period under open channel conditions.

This technique can be used for backwater prediction in the rivers with a distinct spring flood. Its disadvantage is that a ratio between the water level $Z_{Q,a}$ and the water level $Z_{Q,sa}$ (i.e. the level corresponding to the multi-year average water discharge during the spring flood period under open channel conditions) mainly depends on hydraulic parameters of water flow in a certain cross-section which could be non-characteristic for the whole jammed reach, thus, it is likely to get significant errors while calculating water levels caused by ice jams. Moreover, the technique is mainly applicable to the reaches of rivers with small floodplains.

Another technique of backwater calculation, as well developed at SHI [19], uses the empirical relationship between the water level $Z_{JD,Q}$ caused by the ice jam and the river cross-section area $\omega_{JD,Q}$ corresponding to the level $Z_{JD,Q}$:

$$\omega_{JD,Q} = 2.31 \cdot k_p \cdot \xi \cdot (Q_{va} \cdot n_p)^{0.6} \cdot B_{Q,va}^{0.4}, \tag{3}$$

where Q_{va} is the multi-year average water discharge on the river break-up date, m³/s; n_p is the coefficient of riverbed roughness; $B_{Q,va}$ is the river width under discharge Q_{va}, m; k_p is the coefficient of transition from the middle area value to the area value with a predetermined probability of exceedance (it is taken depending on the width $B_{Q,va}$); ξ is the multi-year average coefficient of river bed jamming specified by field observations results (i.e. measurements of the water surface slope, the cross-section areas both during ice jam and under open channel conditions) or by using an empirical function. Usage of this methodology is limited by the complexity and accuracy in determining ξ, Q_{va}, $B_{Q,va}$, k_p.

The most common in hydrological practice technique for backwater calculation is based on the relation of the water surface slope and the average river depth under the water discharge Q and open channel conditions has shown in [20]:

$$\Delta Z = Z_{JD,Q} - Z_{F,Q} = \left(\mu \cdot S_Q^{0.3} - 1\right) \cdot h_Q, \tag{4}$$

where ΔZ is the backwater level excess due to the ice jam, m; $Z_{JD,Q}$ is the maximum water level caused by ice jam under the water discharge Q, m; $Z_{F,Q}$ is the maximum water level under the water discharge Q and open channel conditions, m; μ is the river section jamming coefficient, determined by field measurements, on a basis of the analogy principle or by using reference information (from existing publications); S_Q is the water surface slope under ice jam conditions, ‰; h_Q is the average river depth in the studied cross-section under the water discharge Q and open channel conditions, m.

Based on available measurement data on Q, $Z_{JD,Q}$, $Z_{F,Q}$, h_Q and S_Q, the coefficient μ is calculated also using Equation (4). In the absence of data, the next two techniques are used:

1)   the μ value is calculated by the observation data using the analogy method;
2) μ is specified using a function of the river width increment under ice jam conditions relative to the width under open channel conditions.

Such measurements are complicated and not always can be done out of concern for the safety reasons during ice drift. Thus, characteristics are usually measured only at the governmental network of gauge stations, the number of which is limited, and timing of measurements does not always coincide with the ice jams formation time. The analogy method application during ice jams characteristics determination is not sufficiently substantiated. For that reason, the μ value often contains a great error. A bigger error appears to be while specifying μ by a function from the width increment under ice jams conditions, both due to an approximation of function itself and due to difficulties in specifying the river width during ice jams.

2. Results

We propose a technique for backwater calculation based on schematization of a jammed river longitudinal profile under ice jam conditions as shown in Figure 1.
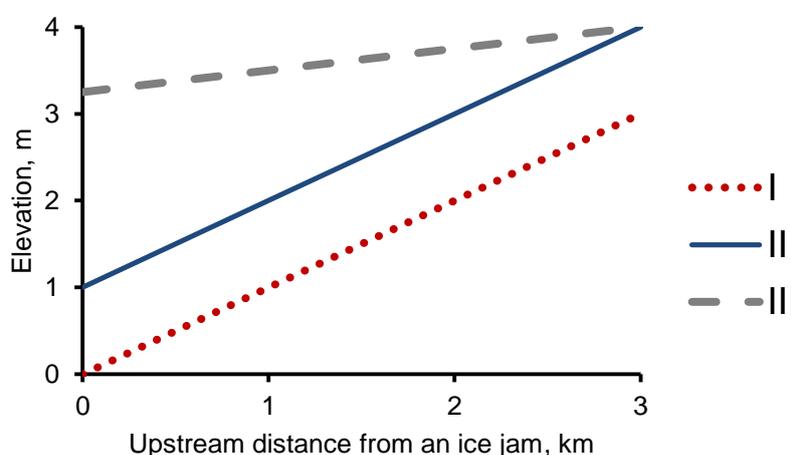
Figure 1. Scheme of the longitudinal profile of a jammed section under a water discharge Q: I – river bottom; II – water surface under open channel conditions; III – water surface under ice jam conditions [21]

The next assumptions have been taken in this technique:
- the backwater value ΔZ is proportional to the water surface slope increment under ice jam conditions relative to water surface slope under open channel conditions:

$$\Delta Z = k_Z \cdot L_J \cdot (S_F - S_J) ,\qquad (5)$$

where k_Z is the proportionality coefficient; L_J is the jammed reach length; S_F and S_J are the water surface slopes under open channel and ice jam conditions, respectively, with the equal water discharge value;
- the water surface slope under open channel conditions S_F is:

$$S_F \approx S_{a,p} \cdot \left(\frac{Q_p}{Q_{ap}}\right)^{k_Q} ,\qquad (6)$$

where $S_{a,p}$ is the weighted average river slope, ‰; Q_p is the water discharge at the ice jam formation moment, m³s⁻¹; Q_{ap} is the multi-year average water discharge, m³s⁻¹; k_Q is the empirical exponent;

- the effective thickness of the ice formations layer Λ is proportional to the ice cover thickness h_Λ:

$$\Lambda \approx h_\Lambda^{k_\Lambda} , \tag{7}$$

where k_Λ is the empirical exponent;

- the maximum possible ice cover thickness Λ_{max} is proportional to the river depth under open channel conditions h_Q:

$$\Lambda_{max} = k_h \cdot h_Q \tag{8}$$

Given the listed assumptions, we obtain:

$$S_J \approx S_F \cdot \left(\frac{h_\Lambda^{k_\Lambda}}{k_h \cdot h_Q + k_S \cdot S_{a,p}} \right) \tag{9}$$

Taking account of (9) we get Equation (5) as:

$$\Delta Z_p = k_Z \cdot \Delta Z_a \cdot \left(\frac{Q_p}{Q_{ap}} \right)^{k_Q} \cdot \left(\frac{\left(k_T \cdot \sqrt{|\sum T_{d,t}|} \right)^{k_\Lambda}}{k_h \cdot h_{Q,p} + k_S \cdot S_{a,p}} \right), \tag{10}$$

where ΔZ_p is the backwater increment under ice jam conditions, m; Q_p is the water discharge at the ice jam formation moment, m³/s; Q_{ap} is the multi-year average water discharge, m³/s; $h_{Q,p}$ is the river depth under open channel and water discharge Q_p conditions, m; $S_{a,p}$ is the weighted average river slope, ‰; $\sum T_{d,t}$ is a sum of the average daily air temperatures at the nearest weather station since the previous calendar year October 1st up to the expected ice jam formation moment, ℃; k_T is the coefficient determined from the reference rivers data using the least squares method based on the ice cover thickness at the end of the ice cover period and a sum of the average daily temperatures since the previous calendar year October 1st up to the moment of ice cover thickness measurement; k_Q, k_Λ, k_h, k_S are coefficients obtained from the reference rivers data by an optimization method, using the measured during ice jam values of backwater increment, water discharge, river depth, ice cover thickness and weighted average river slope; $k_Z \cdot \Delta Z_a$ is the backwater increment average value for research area and river category, determined for the reference rivers using the least squares method.

In the proposed technique, the backwater caused by ice jams characterizes changes in the water and ice balance in a stream reach, which, in turn, is determined by the ratio of thermal and dynamic factors of ice events formation. Equation (10) shows a relation of the actually observed backwater increment ΔZ_p to its average value $k_Z \cdot \Delta Z_a$, typical for one or another natural region. The deviation ΔZ_p from $k_Z \cdot \Delta Z_a$ in Equation (10) is specified by the modular coefficient Q_p/Q_{ap}, the ice cover thickness at the expected time of ice jam formation, the river depth and slope in the control cross-section. Usage of the weighted average slopes, unlike the average ones which were used in the initial equation, and coefficients k_Q, k_Λ, k_h, k_S is more physically reasonable and allows to increase reliability and accuracy of backwater calculation at the studied cross-section.

The calculation methodology for assessment of backwater effects caused by ice jams in the rivers includes: selection of a control cross-section in the jam affected area, assessment of water discharge at the moment of ice jam formation, assessment of multi-year average water discharge, assessment of river depth under open channel conditions corresponding to water discharge at the moment of ice jam formation. In the jam affected reach, the weighted average river slope, the sum of average daily air temperatures since the previous calendar year October 1st up to the moment of ice jam formation are

determined, and then the backwater increment resulting from the ice jam is specified using Equation (10).

The proposed methodology was tested using data from the rivers of Tom (a gauge station at 0.5 km upstream from the city of Tomsk) and Chulym (this river was considered as a reference river). Local river slopes S_j (‰) within individual reaches of l_i (km) length were delineated in the Tom River using an appropriate map, and the weighted average river slope was calculated as $S_{a,p} = 0.31$ ‰. Then the water discharge Q (m^{3}s^{-1}) at the expected ice jam formation moment was estimated as a function of meteorological factors. Water discharges in the Tom River near Tomsk at the ice jam formation moment are shown in Table 1. The multi-year average water discharge Q_a is 1130 m^{3}s^{-1}.

Table 1. Summary table of basic components of the equation (10) and relative errors of the backwater increment ΔZ_p

Date	18.04.2004	29.04.2010	16.04.2013
Water discharge value Q_p, m^{3}s^{-1}	5740	8000	5824
River depth $h_{Q,p}$, m	6.45	7.27	6.49
Ice thickness $h_{\Lambda,p}$, m	0.75	0.90	0.82
Backwater ΔZ_p, m	2.20	3.85	2.45
Relative error ε, %	2	12	10

In the control cross-section at Tomsk city, field measurements were carried out and a relationship between average river depth and water discharge has been constructed. It allowed obtaining the river depth h_Q corresponding to the water discharge Q_p under open channel conditions (Table 1). Ice thickness in the control cross-section is also shown in Table 1.

For the control cross-section of the Tom River at Tomsk the three reference cross-sections at Balakhta, Zyryanskoe and Baturino gauge stations on the Chulym River were selected. The actual observation data set on the rivers of Tom and Chulym allowed obtaining a relationship between the measured values of backwater increment ΔZ_p and a function of hydraulic parameters of the rivers U:

$$U = \left(\frac{Q_p}{Q_{ap}}\right)^{k_Q} \cdot \left(\frac{\left(k_T \cdot \sqrt{|\Sigma T_{d,t}|}\right)^{k_\Lambda}}{k_h \cdot h_{Q,p} + k_S \cdot S_{a,p}}\right) \tag{11}$$

Coefficients k_Q, k_Λ, k_h, k_S, and $k_Z \cdot \Delta Z_a$ were specified using optimization techniques in accordance with hydrologic conditions in the above listed cross-sections and related to the expected ice jam formation moments. For the same cross-sections the multi-year average water discharge values Q_{ap} and the weighted average river slopes $S_{a,p}$ were specified.

Table 2. Multi-year average values of water discharges and weighted average riverbed slopes in modeling cross-sections

Cross-section	Tom River at Tomsk	Chulym River at Baturino	Chulym river at Zyryanskoe	Chulym river at Balakhta
Q_{ap}, m^{3}s^{-1}	1130	782	558	100
$S_{a,p}$, m km^{-1}	0.31	0.25	0.26	0.47

River depths $h_{Q,p}$ and water levels $Z_{F,Q}$ were determined as functions of the water discharge Q_p, and water levels $Z_{JD,Q}$ at the jam formation moment were taken from the measurement data. Backwater increment ΔZ_p under the ice jam conditions is determined as:

$$\Delta Z_p = Z_{JD,Q} - Z_{F,Q} \tag{12}$$

For backwater values determined through Equation (12) and calculated as $\Delta Z_p^* = (k_Z \cdot \Delta Z_a) \cdot U$, a correlation criterion $R^2 > 0.36$ was applied (R2 is a coafficient of determination). In the case when the criterion is not met it is undertaken a repeated selection of coefficients k_Q, k_Λ, k_h, k_S using optimization method. Thus, the parameter values shown in Table 3 were specified for the rivers of Tom and Chulym.

Table 3. Values of parameters for calculation of backwater $\Delta \boldsymbol{Z_p}$

Parameter	$k_Z \cdot \Delta Z_a$	k_Q	k_Λ	k_h	k_S	k_T	S/σ	R^2
Value	0.05	1.45	1.00	0.25	0.60	0.0177	0.59	0.65

For the control cross-section conditions, the final equation for calculating backwater increment caused by an ice jam looks like:

$$\Delta Z_p = (0.50 \pm 0.05) \cdot \left(\frac{Q_p}{Q_{ap}}\right)^{1.45} \cdot \left(\frac{\left(0.0177 \cdot \sqrt{|\Sigma T_{d,t}|}\right)^{1.00}}{0.25 \cdot h_{Q,p} + 0.60 \cdot S_{a,p}}\right) \tag{13}$$

Backwater increments calculated by Equation (13) and relative errors for them are shown in Table 1. The relationship between measured and calculated backwater values is shown in Figure 2.
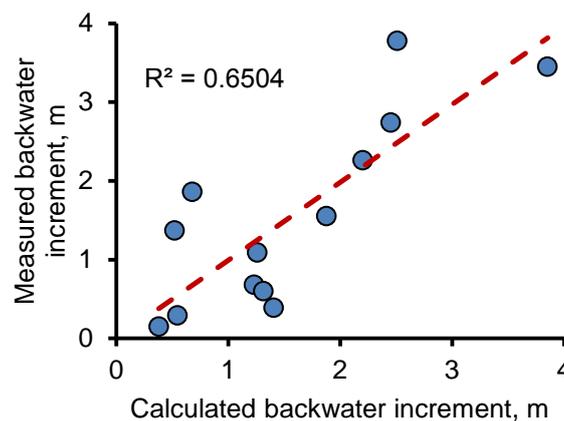
Figure 2. Relationship between measured and calculated backwater values in the rivers of Tom and Chulym

3. Conclusion
The methodology for assessment of backwater increments caused by break-up or freeze-up ice jams in riverbed is proposed. It is based on Equation (10) and reflects the water and ice balance change depending on thermal and dynamic factors of ice jams formation. Backwater calculation using Equation (10) allows planning flood prevention arrangements, both constructional and non-constructional. The accuracy of calculation methodology amounted to 2–12 % of the measured values.

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