

# Modeling Ice-Jam Floods in the Frameworks of an Intelligent System for River Monitoring

I. Krylenko<sup>a, b, c, \*</sup>, A. Alabyan<sup>a, b, c</sup>, A. Aleksyuk<sup>a, b</sup>, V. Belikov<sup>b, c</sup>, A. Sazonov<sup>a, b, c</sup>, E. Zavyalova<sup>a, b</sup>, I. Pimanov<sup>c</sup>, S. Potryasaev<sup>c</sup>, and V. Zelentsov<sup>c, \*\*</sup>

<sup>a</sup>*Faculty of Geography, Moscow State University, Moscow, 119991 Russia*

<sup>b</sup>*Water Problems Institute, Russian Academy of Sciences, Moscow, 119333 Russia*

<sup>c</sup>*St. Petersburg Institute for Informatics and Automation, Russian Academy of Sciences, St. Petersburg, 199178 Russia*

\**e-mail: krylenko\_i@mail.ru*

\*\**e-mail: v.a.zelentsov@gmail.com*

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**Abstract**—The article presents the results of adaptation and application of two-dimensional hydrodynamic model STREAM\_2D to reproduce the characteristics of ice-jam-induced floods in the vicinity of the city of Velikiy Ustyug (the Northern Dvina river basin, Vologda region, Russia). The additional hydraulic resistance due to ice roughness and the decrease in the flow cross-section area due to ice-caused congestion were taken into account for modeling of ice-jam-induced water level variations. The corresponding model parameters were estimated on the basis of numerical experiments and flood modeling for the period from 1980 to 2016, which includes more than 18 significant cases of ice-jamming. Grouping of model parameters by the height of the ice-jam-induced water level rises could be useful for the application of the developed model in the framework of an intelligent information system of river flood monitoring.

**Keywords:** hydrodynamics, river ice, ice-jams, 2D-modeling, flooding, STREAM\_2D, Northern Dvina, Velikiy Ustyug

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## INTRODUCTION

The development of intelligent information systems for monitoring hydrological phenomena is one of the most relevant and promising directions for enhancing both the possibility of flood forecasting, and the awareness of the population allowing the prevention of devastating losses of human lives. Increasingly, mathematical models that are configured to use operational data of hydrometeorological observations, such as Mike Flood Watch [30], Delft FEWS—Flood Early Warning Systems [19], are used as the computational core of such systems. The systems such as Flood Early Warning Systems, European Flood Awareness System (EFAS) [29] cover large regions, often containing a number of states. Similar systems being developed in Russia are more local and focused on solving specific practical problems, such as monitoring and predicting of rain floods in Far East region [13], the propagation of flood waves along large rivers [14], or forecasting water inflow into reservoirs [27]. This situation is due both to the lack of a united governmental support for the automation of hydrometeorological monitoring, and to the great variety of natural conditions in Russia, which require the adaptation of all methods for a specific task. One of these difficult

regional problems, particularly important for the Northern regions, is the monitoring of snowmelt floods complicated by ice-jam events. The determination and prediction of the characteristics of ice-jam floods using complex statistical methods and modeling are challenging because of the lack of observation data and the complex nature of ice-jam flood phenomena [10, 23, 28].

This paper presents the research results related to the development of an intelligent system for monitoring and assessing the state of natural systems (PROSTOR) [4, 31]. The vicinities of the city of Velikiy Ustyug, located at the junction of the Sukhona and Yug rivers, giving the origin to the Northern Dvina River (being called there ‘the Small Northern Dvina’), were chosen as the key area for testing this system (Fig. 1). The vast valleys of these rivers are among the most vulnerable places in Russia to spring snow-melt floods, and ice-jams often induce inundation of lowlands at the city of Velikiy Ustyug and nearby settlements [3]. The monitoring sub-system of PROSTOR allows on-line collecting hydrometeorological data just from the automatic gauges and acquiring actual satellite images. The computational core of PROSTOR is the two-dimensional hydrodynamic model STREAM\_2D [9] and its newer version

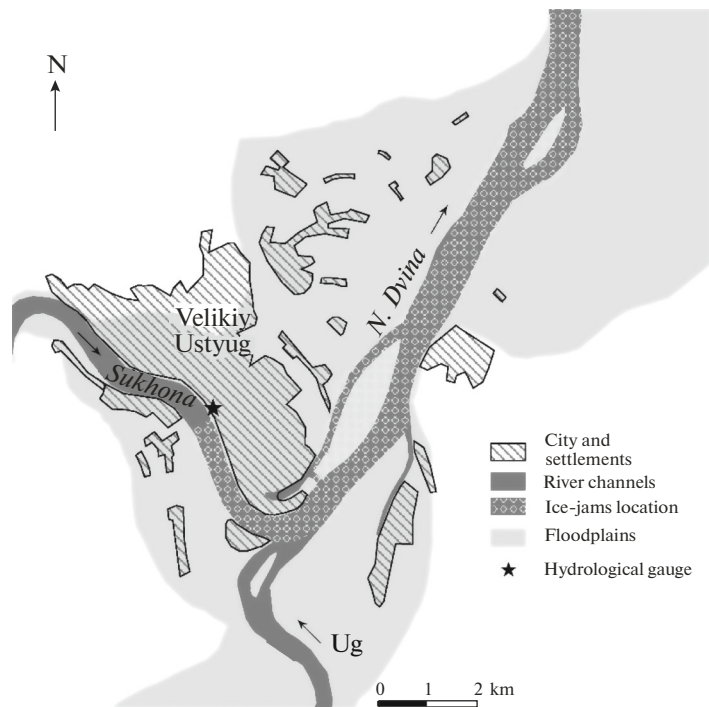


Fig. 1. Study area.

STREAM\_2D\_CUDA [6] based on the numerical solution of shallow-water equations with discontinuous bottom [7]. The forecasting capabilities of the system are secured by the prediction of water levels at the gauging stations located upstream from Velikiy Ustyug either basing on neural networks, or by means of linking with the runoff formation model ECOMAG [27] and using prognostic meteorological information [16]. All results of the system implementation, including the results of flooded zones calculations, flow parameters there, as well as satellite images are available via the geoportal. The technological details of the developed system are set out in a number of papers [4, 31, 32].

The current research is aimed at solving the problem of reproducing the flooding characteristics during ice-jam periods by means of the hydrodynamic modeling technology based on the integration of the entire available operational information domains. Unfortunately, a number of complex theoretical models of freeze-up and breakup periods, the formation and release of ice-jams [18] are difficult to adapt for practical implementation, because they require setting too many parameters, which are difficult to determine online. Therefore, in our research the preference was given to the development of a simplified module of ice-jamming and related phenomena (“ice module”) to be integrated into a hydrodynamic model. This module allows taking into account two main issues of the ice effect: (1) the additional hydraulic resistance due to ice roughness, and (2) a decrease in the flow cross-section area due to ice thickness. A similar

approach is implemented, for example, in the one-dimensional models HEC-RAS [17] and is developing in some two-dimensional models [12]. However, the use of one-dimensional models, such as HEC-RAS, RIVER-ICE [26], in the case of wide floodplains, having very complex configuration, is believed to be not appropriate.

Testing the proposed approach was carried out on the basis of the simulation of long-term series based on the flood observations at Velikiy Ustyug gauge for 37 years (from 1980 to 2016), of which more than 18 years were distinguished by significant ice-jams during the spring breakup period.

The paper has the following structure: Section 1 describes the study area; Section 2 presents the mathematical model and the data used; Section 3 is devoted to the assessment of ice-jam-induced water levels and parameters for their reproduction; Section 4 contains the results of flood simulations for the historical observation period; and in Section 5 an agenda for introducing the proposed approach into the developed monitoring system is discussed.

## THE STUDY AREA

The city of Velikiy Ustyug with a population of about 30 thousand is situated in the northern European Russia at the confluence of the Sukhona and the Yug rivers, where the Northern Dvina originates from their junction (Fig. 1). It is an ancient Russian city founded in the 13th century. Nowadays the urban

areas have spread from terraces to river floodplains, which, together with the location of the city at the junction of large rivers and the high frequency of ice-jamming, predetermines a high danger of flooding. The main causes of the ice-jamming here are almost simultaneous ice breakup over a long reach of the Sukhona river due to its sub-latitudinal orientation and the morphological pattern of the river confluence. There is a sharp bend of the river channel at the area of Velikiy Ustyug and a vast shallow river section abounding with huge sandbars downstream of the junction. One more place of ice-jamming is located in the Small Northern Dvina channel several kilometers downstream near Krasavino settlement.

The floods here are of complex genesis due to snow melting and ice-jams. Ice-jams may cause more than 2–3-m additional elevation in water level, usually ice-jams lasting here from one to five days. The last large floods were observed in 1998, 2013, and 2016 years, and more than half of the city and nearby territories were inundated during these events [1, 2].

Significant efforts are made and considerable material resources are spent in the region every year to prevent ice-jam formation, among them, ice cutting, explosions (including bombing) in the most ice-jam-prone zones, but they could not completely prevent most powerful ice-jams. The region under consideration has been actively studied by hydrologists for the development of measures to reduce flooding hazard [3, 21]. Hydrodynamic modeling was applied to estimate the possible effects of protective levees [1]. The construction of embankment around the city has now begun, but even with this protection, many small settlements on the floodplains will remain in the flooding zone.

## DATA AND METHODS

### Model Description

STREAM\_2D program complex [9] and its newer modification STREAM\_2D CUDA [6], which is based on the numerical solution of two-dimensional Saint-Venant equations, was used for the simulations.

When hydrodynamic models are applied for the period of spring ice cover destruction, ice drift, and the formation of ice-jams, it is necessary to take into account the additional circumstances related to ice movement: the location of usual ice-jams; the maximum length of jam reaches, the roughness factor of ice in jams, a decrease in the flow cross-section area due to filling of the channel with ice; the time of beginning of the ice-jam formation and the duration of its destruction. These factors can be taken into account in the framework of the shallow-water approximation by the following modification of the two-dimensional Saint-Venant equations:

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \\ \frac{\partial(hu)}{\partial t} + \frac{\partial\left(hu^2 + \frac{1}{2}gh^2\right)}{\partial x} + \frac{\partial(huv)}{\partial y} \\ = -gh\frac{\partial b'}{\partial x} + \frac{\tau_1^b + \tau_1^i}{\rho}, \\ \frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial\left(hv^2 + \frac{1}{2}gh^2\right)}{\partial y} \\ = -gh\frac{\partial b'}{\partial y} + \frac{\tau_2^b + \tau_2^i}{\rho}, \end{cases} \quad (1)$$

where  $(x, y)$  and  $t$  are the Cartesian coordinates and time;  $u(x, y, t)$ ,  $v(x, y, t)$ , and  $h(x, y, t)$  are depth-averaged fluid velocity components and the flow depth, respectively;  $b' = b + \rho_i H / \rho$ , where  $b$  denotes the bed level;  $\rho$  and  $\rho_i$  represent water and ice density,  $H$  is ice thickness; vectors  $(\tau_1^b, \tau_2^b)$  and  $(\tau_1^i, \tau_2^i)$  describe the action of the bed and ice surface shear stresses, respectively;  $g$  is the gravitational acceleration.

The derivation of this system from the Navier–Stokes equations is carried out similarly to the derivation of the classical shallow-water equations (ice is considered to be in a floating state; the elastic properties of ice are not taken into account). The bed and ice surface shear stresses can be expressed using the well-known empirical Manning formula with different roughness coefficients ( $n_b$  for bottom and  $n_i$  for ice):

$$\frac{1}{\rho}(\tau_1^b + \tau_1^i, \tau_2^b + \tau_2^i) = -g(n_b^2 + n_i^2)h^{-\frac{1}{3}}\sqrt{u^2 + v^2}(u, v). \quad (2)$$

Thus, the hydrodynamics of such flows can be simulated by solving the classical shallow-water equations by their minor modifications. Firstly, the actual bottom level should be elevated due to the presence of the ice cover. Secondly, the additional term describing the friction on the water and ice contact surface should be taken into account.

The described model was incorporated into STREAM\_2D software, which also allows calculations of sediment transport and riverbed deformations. To start modeling ice-covered rivers using STREAM\_2D it is necessary to input the ice density value additionally to the routine dataset and to prepare special files containing the distribution of ice thickness and roughness coefficient over the modeled area for the entire period of simulation. This is necessary for taking into account the non-stationarity of ice coverage of the water surface, the thickness and roughness of ice. Ice roughness factor should be established by means of model calibration through comparing calculated and observed water levels in control points during periods of ice-jam formation and break up.

### Data Used

The part of the Northern Dvina valley from Velikiy Ustyug to Kotlas city, including the confluence of the Sukhona and Yug rivers, with a total length of about 90 km, is included in the modeling area. Detailed information about the floodplain and riverbed topography was used for model setup. Maps at scales of 1 : 25000 and 1 : 10000 were digitized for the floodplains. Data of the riverbed relief were obtained from detailed field surveys organized by the Lab of Soil Erosion and River Channel Processes of the Geography Faculty of Lomonosov Moscow State University. Data of measured flow velocities and water surface slopes obtained during the field campaigns were implemented for model calibration and verification as a first step.

The discretization of the modelling area in STREAM\_2D consists of an irregular hybrid computational mesh with a spatial resolution from about  $40 \times 40$  m for the river channels, from 40 to 300 m for the floodplains depending on the available topographic information. The computational domain contains more than 50000 cells.

The data from the gauges of the river Sukhona–Kalikino (the basin area is 49200 km<sup>2</sup>) and the river Yug–Gavrino (the basin area is 34800 km<sup>2</sup>) are used to setup the daily water discharges at the upper boundary of the model. The gauge Gavrino on the river Yug was closed in 1989, and for the later period we have to use the data of gauges from the upper reaches of the river Yug basin (Yug river–Podosinovets and its tributary Luza–gauge Krasavino). Water levels for the gauges located in the city Velikiy Ustug were used as control point for model calibration and validation. A map of typical places of ice-jam formation was compiled on the basis of the historical data and satellite images, the dates of the ice-jams formation were taken according to the hydrological gauges data. The satellite images were also used for additional validation of the model through comparison of the observed and modelled flooded zones for outstanding flood events [31].

In this research, a model calibrated and validated during our previous researches [1, 31] was used for establishing ice-jam module parameters, appropriate for the modeling on the base of long-term period data of the hydrological observation from the 1980 to 2016.

### ASSESSMENT OF ICE-JAM-INDUCED WATER LEVEL RISES AND THE RANGE OF MODEL PARAMETERS FOR THEIR SIMULATION

The theoretical background for the identification of water level rises induced by ice-jams from the total growth of water surface elevation throughout spring snowmelt flood is represented by the concept of water levels genetic components, developed by N.I. Alekseevsky and his colleagues [3, 5]. The key point of this

concept is so-called ‘genetic water level equation’ reflecting the fact that the total flood water level mark  $H$  can be expressed as a sum of main constituents, determined from river runoff (“runoff level”  $H_Q$ ), induced by ice jams (“ice-jam level”  $\Delta H_{ij}$ ), or backwater effect of tributaries (“back-water level”  $\Delta H_{bw}$ ):

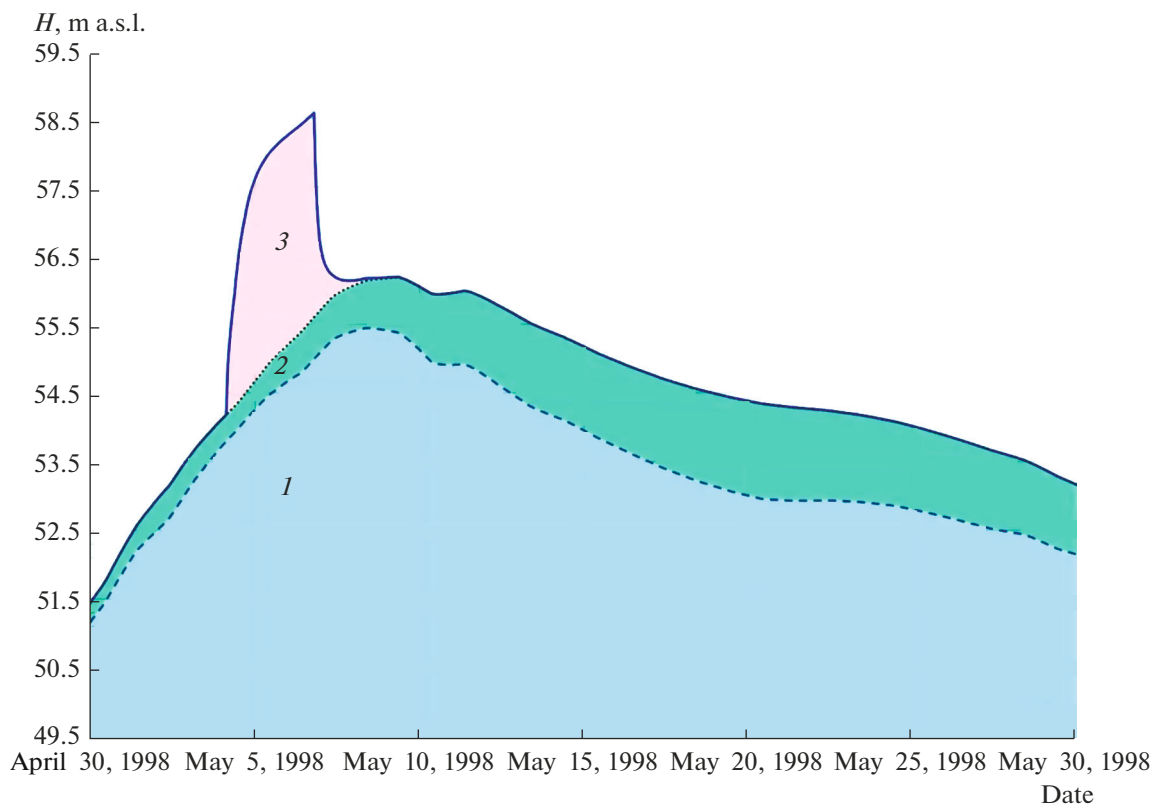
$$H = H_Q + \Delta H_{ij} + \Delta H_{bw}. \quad (3)$$

As well, equation (3) can include some components appearing as a result of fluvial processes or man-made activities. For the river mouths components, concerning water level rising due to tidal waves, wind surges also can be important, but they are not relevant for the study area.

Estimates of the water levels genetic components at the city of Velikiy Ustyug based on hydrodynamic modeling [24] has revealed that the essential component of maximum water level rises is the runoff-determined water level, for example 1%-occurrence water discharges can pass with water level up to 787 cm (57.21 m above sea level) above gauge zero (49.34 m a.s.l.). Significant contribution to the additional increase in water level just near the city of Velikiy Ustyug can be linked with ice-jams. They always form only during the growth of the Sukhona runoff and never persist to the peak flow. The maximum water levels during ice-jams formation can be higher than 900 cm above the zero level of the Velikiy Ustug gauge. The water levels, close to the historical maximum were observed in 1998 and 2016 (mean daily levels were 933 cm and 916 cm above gauge zero level, respectively), and were connected with ice-jam formation and input runoff of the Sukhona river higher than the average values during ice-jamming period.

The backwater effect from the Yug river is relatively small in terms of additional water level rise (0.5–0.8 m) at the Sukhona runoff maximum, but can increase significantly (more than 1 m) after passing through the peak (Fig. 2). The common features of temporal changes in water level components throughout the snowmelt floods for this area is similar from year to year.

Simulations of the outstanding floods of 1998 and 2016 have demonstrated that by means of the incorporation of the ice module considering the additional parameters such as ice roughness and thickness into the hydrodynamic model, it is possible to reproduce the temporal variations of the levels during the ice-jam period with a high accuracy [24]. The scenario calculations with switched on/off ice module allow evaluating ice-jam-induced water level rising  $\Delta H_{ij}$ ; if we decrease the inflow from the Yug river, we can, by the same scenario approach, estimate the water level rise  $\Delta H_{bw}$ , induced by backwater phenomena and as a result, we obtain the pure runoff determine runoff level  $H_Q$  (Fig. 2).



**Fig. 2.** Example of segregation of genetic components of water levels for the flood period of 1998 year at the river Sukhona—gauge Velikiy Ustyug according results of scenario modeling: 1—river runoff determined water level ( $H_Q$ ), 2—additional water level rising due to backwater phenomena from the river Yug ( $\Delta H_{bf}$ ); 3—ice-jam induced water level rising ( $\Delta H_{ij}$ ).

After the successful simulation of most hazardous floods, an attempt was made to simulate the temporal series containing a chain of successive real years. As a result, it was found, that, if the parameters adjusted for outstanding ice-jams are applied to the entire time series, it will lead to significant overestimation of the maximum simulated water level marks. Therefore, at the first stage, all ice-jam water level rises have been analyzed for the entire observation period from 1980 to 2016. This was carried out by means of scenario simulations with switched off ice module. Taking into account the fact that the open water levels are reproduced by the model with a high accuracy [1, 31], the maximum observed levels of ice-jam-related floods were compared with the simulated levels without ice-jamming for the same dates, and ice-jam-induced water levels rises were calculated as their differences (Table 1).

It was found that the value of ice-jam rise in water levels varies significantly in different years (from 1 to 3.8 m). From the analyzed 18 floods, in seven cases, ice-jam-induced water level rise was higher than 2.5 m, and from them three events are characterized by ice-jam-induced water level rise higher than 3 m (1992, 2013, and 2016). Seven events are characterized by the ice-jam-induced water level rise in the range

from 1.5 to 2.5 m, and during the rest ones, additional water level rise was less than 1.5 m. Several ice-jamming cases with insignificant water levels in 1981, 1986, 2000, and 2009 were not included in the analyzed ice-jam data set.

The described results allow us to justify the use of various groups of model parameters reflecting an additional increase in the roughness coefficient and a decrease in the flow cross-section depending on ice-jam-induced water level rise.

To assess the model sensitivity and the possible range of the ice module parameters, a number of numerical experiments was conducted for realistic reproduction of different ice-jam levels over the entire modelled area. The additional ice roughness was set so as to comply with the ordinary Manning roughness coefficient range for ice conditions from 0.035 to 0.125 [8, 25] with increments of 0.01. The additional reduction of the channel cross section area by the ice thickness was simulated to be zero, 1 m, and 2 m. As the upper boundary conditions, the mean water discharges of the Sukhona and Yug rivers for the ice-jam peak days were taken (1770 and 630 m<sup>3</sup>/s, respectively), and the duration of the ice-jam period was supposed to be 2 days. The results of these numerical

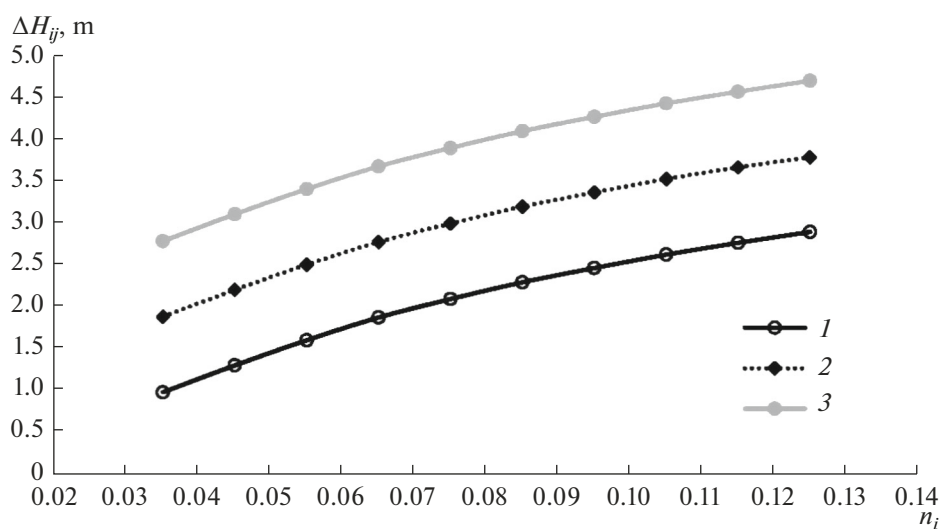
**Table 1.** Results of ice-jam induced water level rising assessment at the gauge Velikiy Ustyug for period of observations

Year	Dates of ice-jam formation	Input discharges of the rivers at the ice-jam peak, m <sup>3</sup> /s		Ice-jam induced water level rise according results of scenario modeling, m	Type of ice-jam according water level rise
		Sukhona	Yug		
1982	April, 20–22	1430	324	1.50	2
1983	April, 3–4	1870	790	1.75	2
1984	April, 19–21	1820	672	2.74	3
1985	April, 27–29	1140	1000	2.52	3
1988	April, 18–21	999	555	1.21	1
1989	April, 15–20	1620	110	1.54	2
1990	April, 9–12	1390	494	1.14	1
1991	April, 14–16	2900	1185	2.22	2
1992	April, 16–20	2200	625	3.45	3
1996	April, 26–May, 1	1483	178	1.18	1
1998	May, 3–6	3910	1017	2.87	3
2001	April, 13–16	974	456	2.50	3
2002	April, 20–21	1340	532	2.05	2
2004	April, 16–19	2000	262	1.40	1
2005	April, 16–18	1490	871	2.40	2
2010	April, 15–17	1390	534	2.32	2
2013	April, 23–25	2120	785	3.80	4
2015	April, 18–19	759	125	0.94	1
2016	April, 14–18	2770	1424	3.60	4

experiments were summarized in the form of a nomogram (Fig. 3).

It was obtained that with an increase in roughness at the places of the ice-jams for 0.01 the water level at

the control point located at the gauging station of Velikiy Ustyug rises from 0.3 m at the additional roughness of 0.035 and only to 0.15 m at the highest values of the additional roughness. The dependence of the addi-



**Fig. 3.** Ice-jam induced water level rising ( $\Delta H_{ij}$ ) at the gauge Velikiy Ustug for different values of additional ice roughness ( $n_i$ ) received as results of numerical experiments with two-dimensional hydrodynamic model: 1—without ice thickness consideration, 2—with ice thickness 1 m, 3—with ice thickness 2 m.

**Table 2.** Parameters of ice module, received for different heights of ice-jam induced water level rising near city Veliky Ustyug

No.	Type of ice-jam	Ice-jam induced water level rise, m	Ice roughness coefficient, $n_i$	Ice thickness parameter, m
1	Small	<1.5	0.045	1
2	Medium	1.5–2.5	0.045	1.5
3	Congestion	2.5–3.5	0.075	2
4	Catastrophic	>3.5	0.100	2

tional water level rise caused by ice-jam from the ice roughness can be approximated by a logarithmic curve. The maximum water level rise at the gauge Velikiy Ustyug, which can be caused by the roughness increasing up to the maximum values alone, is about 2.9 m. The further increase of the roughness coefficient will result in values of this parameter significantly outside of the natural range. The additional water level rise can be obtained by the taking into account by the constraint of the channel cross-section area by the ice. It should be mentioned, that maximum values of ice-jam induced water level rise, presented on the diagram is higher, than observed values, because the described experiment design considers constant conditions of the input water flow and ice-jam position during two days, which is practically never observed during spring floods formation. The next chapter is described dynamic flood modeling taking into account real flood conditions.

## RESULTS OF FLOOD SIMULATION FOR THE LONG-TERM PERIOD

Analysis of the received nomogram (Fig. 3) shows that, in principle, for any value of ice-jam level, it is possible to choose the best possible set of the ice module parameters. However, setting individual parameters for each year does not correspond to the actual research strategy. For example, if the intellectual system should be switched to the forecasting mode, the exact value of the ice jam level would be not known, and at best, only the approximate evaluations of the forming jam could be used.

Therefore, the Buzin's classification of ice jams [15] was adapted to distinguish 4 types ice-jam induced water level rising: (1) small jams are characterized by water level rise less than 1.5 m, (2) medium jams—1.5–2.5 m, (3) congestion jams—2.5–3.5 m, and (4) catastrophic jams—more than 3.5 m (Table 1). This approach allows to make a choice of the optimum set of ice module parameters when modeling long-term series.

Modeling period from 1980 to 2016 years was divided onto two part: 1980–1998 was used for calibration of ice module parameters, 1999–2016 for the model verification. The modelling was carried out only for the high water period from April 1 to June 30

of each year, which covered the passage of high waters and period ice-jam formation.

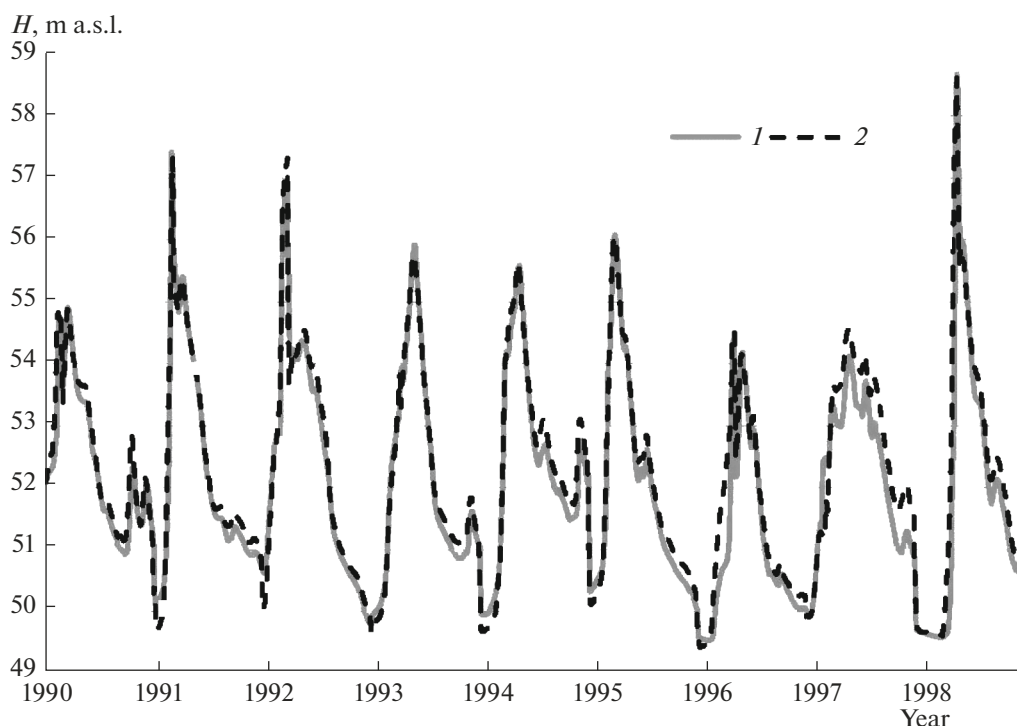
Due to the some shifting of the floods in time from year to year, the period from the beginning of April also includes several days with steady ice conditions before ice break. Separate study for the winter freeze up conditions was not conducted in the presented research, because in this period water levels and discharges are many times below than ice-jams induced. However, for their reproducing during modeling the same approach was used, and ice module parameters were set as follows: ice thickness was set according mean average values as 0.7m, ice roughness was set as 0.035.

Water levels for the open water conditions, which also take place in the considered periods of each year, model reproduces well with channel roughness coefficient 0.025, which value was obtained during model calibration and verification on the previous stage of researches [1, 31].

For the period of calibration the parameters of ice module, which are provide the better coincidence of simulated and observed water levels for the gauge Velikiy Ustyug, were determined according heights of ice-jam induced water level rising (Table 2). Ice-jam induced water levels rising less than 1.5 m (type 1) is better reproducing with additional ice roughness coefficient 0.045 and ice thickness parameter 1 m; for medium (type 2) ice jams reproducing ice thickness parameter should be increased up to 1.5 m. Congestions ice jams (type 3) with water level rise more than 2.5 m and less than 3.5 m were good reproduced with ice roughness coefficient 0.075 and ice thickness parameter 2 m. Such floods were observed during the calibration period in 1984, 1992 and 1998 years.

Using described set of parameters, satisfactory coincidence of the simulated and observed daily water levels for the gauge Velikiy Ustyug was received (Fig. 4). Nash-Sutcliffe coefficient (NSE) value for the days with ice-jams formation (more than 40 days for the whole period) is 0.72, for the all calibration period including freeze up, break out and open water periods NSE criteria value is 0.94 (Table 3). To obtain good correspondence of simulated and observed water levels during ice-jams period, it is important to set not only ice module parameters, but also correctly set up the time of ice-jam formation and destruction,





**Fig. 4.** Daily observed (1) and simulated (2) water levels ( $H$ ) at the gauge Velikiy Ustyug (only periods of each year from April 1 till June 30).

because ice-jam induced water level peaks have very sharp configuration.

Period of 1999–2016 years was used for the model verification on the base of set of obtained parameters. During this period, two outstanding floods of 2013 and 2016 years were observed. The height of ice-jam induced water level rising during mentioned events was higher than 3.5 m, such water level rising was not observed during calibration period and were considered as catastrophic ice-jams (type 4). At the value of the ice roughness coefficient 0.075 the peaks of these floods were underestimated, for the better reproducing of maximum water levels of such catastrophic ice-jams event ice roughness should be set about 0.1.

For the period of verification Nash–Sutcliffe coefficient for the days with ice-jams induced water levels was 0.79, for the whole period of 1999–2016 its value is 0.91. Slightly less value of NSE for the period of verification in comparison with calibration period is not

connected with ice-jams periods. More likely it is associated with a lower accuracy of the data on the water discharges due to fact, that the nearest to the river confluence gauge Gavrino–river Yug was closed in 1989, and for later period we have to reconstruct water discharges of the Yug river using data of the upstream gauges.

The maximum year water levels for the period of observation were analyzed separately (Fig. 5), because it is the most important characteristic for delineation of the flooding hazard. The model reproduced them sufficiently good; the Nash–Sutcliffe efficient criteria value for maximum water levels for 1980–2016 years period is 0.92, the mean value of the absolute deviations of the simulated maximum water levels from the observed ones is 18 cm.

Analysis of the temporal row of maximum water levels for 1980–2016 years has shown, that ice-jam induced water levels are determined maximum year water levels values in 15 cases from 18 considered ice-jam events. The maximum water levels of outstanding floods (such as 1998) usually correspond with high value of ice-jam induced water level rise (more than 2.5 m) with input runoff above the average values or with catastrophic ice-jam (such as 2013). The recent flood of 2016 year is characterized both by the increased value of runoff input and by catastrophic value of additional ice-jam induced water level rising.

**Table 3.** Efficiency criteria (NSE) received for comparison of observed and simulated daily water levels at the gauge station Velikiy Ustyug

Period	Years	Days with ice-jams formation	All
Calibration	1980–1998	0.72	0.94
Verification	1999–2016	0.79	0.91



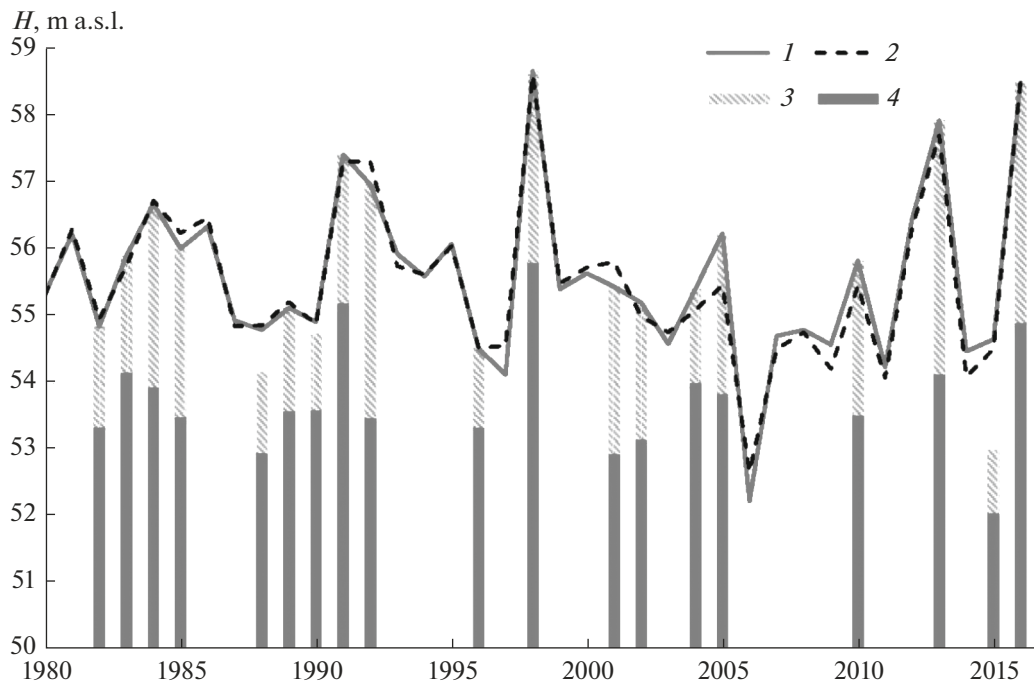


Fig. 5. Comparison of maximum year observed (1) and simulated (2) water levels at the gauge Veliky Ustug for the period 1980–2016 years; determined as result of scenario modeling maximum additional ice-jam induced water level rising ( $\Delta H_{ij}$ ) (3); sum of runoff and backwater determined water levels ( $H_Q + \Delta H_{bf}$ ) in the years with ice-jam formation (4).

## DISCUSSION

The proposed approach based on typification of ice-jams allows to reproduce variation of water level marks during snowmelt spring floods at Veliky Ustug for the entire historical series of observations from 1980 to 2016 years with satisfactory accuracy. So, it is getting possible to estimate boundaries of flooded areas by means of two-dimensional hydrodynamic modeling even during the period of ice-jam formation, existence and breakthrough. Comparison of inundated areas resulting from the simulation with satellite images for outstanding floods also confirms the reliability of this modeling approach [1, 31].

When the monitoring system is working in real-time mode the proposed sets of parameters can be applied as follows: the ice module parameters for the largest and catastrophic ice-jams (set 4) should be used to demonstrate the maximum possible water levels and flooding zone limits in the current situation (it is better to overestimate the danger than to underestimate it). The resulting value can be updated according to operational information, including expert opinions about the ice jam congestion. A very promising seems to be the possibility of automated selection of the ice module parameters according to the difference of the observed water level and its value simulated for the same conditions but without the ice phenomena (“open water level”). In this case, both parameter sets for different types of ice-jams, and proposed kind of nomograms can be used to choose appropriate for the

current situation values of ice module parameters. If enough computational resources are available (currently the system executes the simulation every 15 min), the parameters of the ice module from the specified range can be refined online using multivariate calculations.

It is necessary to notice that on the current stage of the modeling system development the locations and boundaries of river reaches of possible spring ice jams formation should be input a priori, and only maps of typical ice-jam location was used during simulations. However, ice-jam length can change significantly both from year to year, and during the same event. The precise location of the jam boundaries is of great importance for water level along the stretch upstream from the jam. In the future, with the development of a subsystem based on automated processing of satellite images, the boundaries of forming ice jams can be refined in real time mode and urgently transferred to the model, although the decoding routines for identification between the plain ice cover and ice jam are only under development worldwide [33]. In this case, the possibilities of crowdsourcing data collection as a part of the system could also be useful. The observed data about ice-jam forming can be transmitted by the similar way as users can transmit data about their observations of the land inundation in critical points (flooded/not flooded, ice-jam/no ice-jam).

The prediction and modeling of the very fact of the ice-jam formation, which is a separate and very serious

scientific problem [2, 15], stay beyond the scope of this study. However, in the modes of monitoring and short-term forecast (up to 48 hours), to which the system is currently configured, the information on ice-jams can be obtained from the regional hydrometeorological network. The information about first ice-jam formation after ice drift beginning can be considered as a signal for switching-on the ice module at the proper phase of the water regime (flood rise). Another possibility to switch on the ice module could be a sharp increase of water level at Veliky Ustyug gauging station (more than 70–90 cm per day) that can indicate the ice-jam formation.

The methodological developments concerning the gradations of water level rises induced by ice-jams and corresponding sets of parameters for ice module of the hydrodynamic model are regional by their nature and may differ somewhat along other sections of river valleys. For example, the effect of the flow cross section reduction due to ice can be neglected at large rivers where the channel depth is much larger than ice thickness. This circumstance was noted when the similar model with ice module was applied for the Lena river near the city of Yakutsk, where the channel depth is up to 20 m. For that case study, ice-jams were modeled only by specifying additional ice roughness [22].

General approaches for ice-jam effect modeling, which have been developed as a result of this study, can be used in solving similar problems in other regions. The adaptation of two-dimensional hydrodynamic model for taking into account ice conditions should include the following steps:

identification of river stretches where ice-jams usually form;

determining the limits of water level rises induced by ice-jams by the analysis of the historical series using scenario simulations;

numerical experiments for estimating the ice-jam level rises with different sets of parameters for ice module of the hydrodynamic model;

calibration of ice module parameters (with separation of ice-jams into different types or without it);

verification of ice module parameters using the independent data sets.

## CONCLUSIONS

On the basis of the STREAM\_2D software with implementation of developed ice module, a multi-year series of ice-jams floods for a complex area of the confluence of the Sukhona and Yug rivers were simulated.

Based on the results of scenario modeling it was determined that ice-jams induced additional water level rising can exceed at the gauge Velikiy Ustyug the heights of 3.8 m. Numerical experiments have shown that observed for the historical periods ice-jam induced water levels can be reproduced during modeling with a range of additional ice roughness coeffi-

cients from 0.045 to 0.1 and ice thickness parameter from one to 2 m.

For setting of the optimum values of ice module parameters according ice-jams induce water level rising all ice jams were classified as follows: 1—small jams with water level rise less than 1.5 m; 2—medium jams (water level rise 1.5–2.5 m); 3—congestion jams (water level rise 2.5–3.5 m); 4—catastrophic jams (water level rise more than 3.5 m).

Results of the model calibration on the base of data for the period of 1980–1998 years and the model verification for period 1999–2016 years have demonstrated, that the model can reproduce ice-jam induced water levels with satisfactory quality (NSE criteria for the days with ice-jam formation was 0.72 and 0.79 correspondingly). The model results for the period under study are also well enough in term of comparison of maximum year water levels with observed ones (NSE = 0.92).

Analysis of ice-jam induced water level rises for the period of observation has showed that the maximum water levels were due either to a combination of increased runoff during the ice-jam period with congestion ice-jam (1998) or a catastrophic ice-jam (2013). In the 2016 year, extreme flood was determined by the both factors simultaneously.

For the implementation of the developed approach within the framework of the operational flood monitoring system, at the first stage it is recommended to use defined sets of ice module parameters. The maximum possible height of ice-jam induced water levels should be estimated based on maximum values of parameters for catastrophic ice-jams. At the next stage of research, the approach, than the parameters of the ice module from the specified range can be refined online using multivariate calculations can be developed.

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## REFERENCES

1. Agafonova, S.A., Frolova, N.L., Krylenko, I.N., Sazonov, A.A., and Golovlyov, P.P., Dangerous ice phenomena on the lowland rivers of European Russia, *Natural Hazards*, 2017, vol. 88 (S1), pp. 171–188. <https://doi.org/10.1007/s11069-016-2580-x>
2. Agafonova, S.A., and Frolova, N.L., Ice jam floods on the Sukhona R. in the area of Velikiy Ustyug, in *Menyayushchiysya klimat i sotsial'no-ekonomicheskii potentsial Rossiyskoi Arktiki* (The Changing Climate and So-

- cio-Economic Potential of the Russian Arctic), vol. 2, Sokratov, S.A., Ed., Moscow: Liga-Vent, 2016. pp. 56–65.
3. Alabyan, A.M., Alekseevsky, N.I., Evseeva, L.S., Zhuk, V.A., Ivanov, V.V., Surkov, V.V., Frolova, N.L., Chalov, R.S., and Chernov, A.V., Genetic analysis of the causes of the spring flooding of the valley of the Small Northern Dvina in the area of the city of Velikiy Ustyug, in *Eroziya pochv i ruslovyye protsessy* (Soil Erosion and Channel Processes), Moscow, 2003, vol. 14, pp. 105–131.
  4. Alabyan, A.M., Krylenko, I.N., Potryasaev, S.A., Sokolov, B.V., Yusupov, R.M., and Zelentsov, V.A., Development of intelligent information systems for operational riverflood forecasting, *Herald Russ. Acad. Sci.*, 2016, vol. 86, no. 1, pp. 24–33. <https://doi.org/10.1134/S1019331616010056>
  5. Alekseevsky, N.I., Obodovskiy, A.G., and Samokhin, M.A., Mechanisms of changes in water levels in rivers, in *Eroziya pochv i ruslovyye protsessy* (Soil Erosion and Channel Processes), Mosk. Gos. Univ., 2005, vol. 4. pp. 216–237.
  6. Alekseyuk, A.I., and Belikov, V.V., *Programmnyi kompleks STREAM\_2D CUDA dlya racheta techenii, deformatsii dna, i perenosha zagryaznenii v otkrytykh potokakh s ispol'zovaniem tekhnologii CUDA (na graficheskikh protsessorakh NVIDIA)* (Software Complex STREAM\_2D CUDA to Calculate Streams, Bottom Deformation, and Pollutant Transfer in Open Flows Using CUDA Technology (on NVIDIA GPUs)), (SOFT) Software State Registration Certificate no. 2017660266, Russian Agency for Intellectual Property, 2017.
  7. Alekseyuk, A.I. and Belikov, V.V., The uniqueness of the exact solution of the Riemann problem for the shallow water equations with discontinuous bottom, *J. Comput. Phys.*, 2019, vol. 390, pp. 232–248. <https://doi.org/10.1016/j.jcp.2019.04.001>
  8. Baryshnikov, N.B., *Rukovodstvo k laboratornym rabotam po dinamike ruslovykh potokov i ruslovykh protsessam* (Guide for Laboratory Studies of the Dynamics of Channel Flows and Channel Processes), Leningrad: Gidrometeoizdat, 1991.
  9. Belikov, V.V. and Kochetkov, V.V., *Programmnyi kompleks STREAM-2D dlya rascheta techenii, deformatsii dna i perenosha zagryaznenii v otkrytykh potokakh* (Software Complex STREAM\_2D to Calculate Streams, Bottom Deformations, and Pollutants Transfer in Open Flows), Software State Registration Certificate no. 612181, Russian Agency for Intellectual Property, 2014.
  10. Beltaos, S., Hydrodynamic characteristics and effects of river waves caused by ice jam releases, *Cold Reg. Sci. Technol.*, 2013, vol. 85, pp. 42–55. <https://doi.org/10.1016/j.coldregions.2012.08.003>
  11. Borsch, S.V., Gelfan, A.N., Moreydo, V.M., Motovilov, Yu.G., and Simonov, Yu.A., The long-term ensemble forecast of the spring inflow of water to the Cheboksary Reservoir based on the hydrological model: the results of the verification and operational tests, in *Trudy Gidrometeorologicheskogo nauchno-issledovatel'skogo tsentra Rossiyskoy Federatsii* (Trans. Hydrometeorological Research Center of the Russian Federation), 2017, vol. 366, pp. 68–86.
  12. Brayall, M. and Hicks, F.E., Applicability of 2-D modeling for forecasting ice jam flood levels in the Hay River Delta, Canada, *Can J. Civ. Eng.*, vol. 39, no. 6, 2012, pp. 701–712. <https://doi.org/10.1139/12012-056>
  13. Bugaets, A.N., Gonchukov, L.V., Sokolov, O.V., Gartsman, B.I., and Krasnopeyev, S.M., Automated information system for hydrological monitoring and data management, *Meteorol. Gidrol.*, 2017, no. 3, pp. 103–113.
  14. Burakov, D.A., Kosmakova, V.F., and Volkovskaya, N.P., Procedure for long-term forecast of maximum water levels for the Ob River near the city of Nizhnevartovsk and the results of its testing, *Rezultaty ispytaniya novykh i usovershenstvovannykh tekhnologiy, modeley i metodov gidrometeorologicheskikh prognozov* (Test Results of New and Improved Technologies, Models and Methods of Hydrometeorological Forecasts), 2017, no. 42, pp. 50–59.
  15. Buzin, V.A., *Zazhory i zatory l'da na rekakh Rossii* (Ice Gorges and Ice Jams on the Russian Rivers), St. Petersburg: Gos. Gidrol. Inst., 2015.
  16. Churiulin, E.V., Krylenko, I.N., Frolova, N.L., and Belyaev, B.M., Research of opportunities of combined use of the runoff formation Ecomag model and meso-scale atmosphere circulation cosmo-ru model (on the example of floods on the Sukhona river at the Velikiy Ustyug), *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 263, pp. 1–7. <https://doi.org/10.1088/1755-1315/263/1/012057>.
  17. Daly, S., and Vuyovich C.M., Modeling river ice with HECRAS, in *Proc. the 12th CGU-HS CRIPE Workshop on River Ice*, Edmonton, 2013, Alta, p. 11.
  18. Debolskaya, E.I., *Matematicheskie modeli ledovykh zatorov i ikh posledstviy* (Mathematical Models of Ice Jams and Their Consequences), Moscow: RUDN Press, 2014.
  19. Delft-FEWS: A platform for real time forecasting and water resources management. <https://www.deltares.nl/en/software/flood-forecasting-system-delft-fews-2/> (Accessed June 15, 2019).
  20. Frolov, A.V., Asmus, V.V., Borsch, S.V., Vilfand, R.M., Zhabina, I.I., Zatyagalova, V.V., Krovotintsev, V.A., Kudryavtseva, O.I., Leontyeva, E.A., Simonov, Yu.A., and Stepanov, Yu.A., GIS-Amur system of flood monitoring, forecasting, and early warning, *Russ. Meteorol. Hydrol.*, 2016, vol. 3, pp. 157–169.
  21. Frolova, N.L., Agafonova, S.A., Zavadsky, A.S., and Krylenko, I.N., Hazard assessment of hydrological phenomena at the regional and local levels, *Vodnoye khozyaystvo Rossii: problemy, tekhnologii, upravleniye* (Russian Water Industry: Problems, Technologies, Management), 2014, no. 3. pp. 58–74.
  22. Kornilova, E.D., Krylenko, I.N., Golovlyov, P.P., Sazonov, A.A., and Nikitsky, A.N., Verification of the two-dimensional hydrodynamic model of the Lena River near Yakutsk according to time-based space imagery data, *Sovremennyye problemy distantsionnogo zondirovaniya Zemli iz kosmosa* (Modern Problems of Remote Sensing of the Earth from Space), 2018, vol. 15, no.5, pp. 169–178. <https://doi.org/10.21046/2070-7401-2018-15-5-169-178>

23. Kovachis, N, Burrell, B.C., Huokuna, M., Beltaos, S., Turcotte, B., and Jasek, M., Ice-jam flood delineation: Challenges and research needs, *Rev. Canad. Ressour. Hydriques*, 2017, vol. 42, no.3, pp. 258–268. <https://doi.org/10.1080/07011784.2017.1294998>
24. Krylenko, I.N., Agafonova, S.A., and Sazonov, A.A., Evaluation of genetic components of water levels, in *Gidrometeorologiya i ekologiya: nauchnyye i obrazovatel'nyye dostizheniya i perspektivy razvitiya* (Hydrometeorology and Ecology: Scientific and Educational Achievements and Development Prospects), St. Petersburg: Agraf+, 2017, pp. 288–292.
25. Levi, I.I., *Zimnii rezhim rek. Konspekt lektsii po III chasti kursa inzhenernoi gidrologii* (Winter Regime of Rivers. Lectures on Engineering Hydrology), Leningrad: Hydrometeoizdat, 1958.
26. Lindenschmidt, K.-E., RIVICE—a non-proprietary, open-source, one-dimensional river-ice model, *Water*, 2017, vol. 9 no. 5, p 314. <https://doi.org/10.3390/w9050314>
27. Motovilov, Yu.G., Balyberdin, V.V., Hartsman, B.I., Gelfan, A.N., Moreydo, V.M., and Sokolov, O.V., Short-term forecast of water inflow to the Bureya Reservoir based on the ECOMAG model and using meteorological forecasts, *Vodnoye khozyaystvo Rossii: problema, tekhnologii, upravleniye* (Russia's Water Industry: Problems, Technologies, Management), 2017, no. 1, pp. 78–102.
28. Rokaya, P., Budhathoki S., and Lindenschmidt K.E., *Natural Hazards*, 2018, vol. 94, no. 3, pp. 1439–1457. <https://doi.org/10.1007/s11069-018-3455-0>
29. Romanov A.V., Development of a flood forecasting system in the Russian Federation, Part 1, Background and catalysts of changes, *Trudy Gidrometeorologicheskogo nauchno-issledovatel'skogo tsentra Rossiyskoy Federatsii* (Proc. Hydrometeorological Research Center of the Russian Federation), 2017. vol. 365, pp. 182–195.
30. Skotner, C., Klinting, A., and Ammentorp, H., Mike Flood Watch—managing real-time forecasting. [http://dhigroup.com/upload/publications/mike11/Skotner\\_MIKE\\_FLOOD\\_watch.pdf](http://dhigroup.com/upload/publications/mike11/Skotner_MIKE_FLOOD_watch.pdf) (accessed August 15, 2018).
31. Zelentsov, V., Pimanov, I., Potryasaev S., Sokolov, B., Cherkas, S., Alabyan, A., Belikov, V., and Krylenko, I., River flood forecasting system: An interdisciplinary approach, in *Flood Monitoring through Remote Sensing*, 2018, Springer, Cham Cham, pp. 81–100. [https://doi.org/10.1007/978-3-319-63959-8\\_4](https://doi.org/10.1007/978-3-319-63959-8_4)
32. Zelentsov, V. and Potryasaev, V.A., Architecture and examples of implementing the informational platform for creation and provision of thematic services using earth remote sensing data, *Trudy SPIIRAN* (Proceeding SPIIRAS), 2017, vol. 6 no. 55, pp. 86–113. <https://doi.org/10.15622/sp.55.4>
33. Zhang Fan, Mosaffa, M., Chu Thuan, Lindenschmidt, K.E., Using Remote Sensing Data to Parameterize Ice Jam Modeling for a Northern Inland Delta, *Water*, 2017, vol. 9 no. 5, p. 306. <https://doi.org/10.3390/w9050306>