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Engineering hydrology technologies to reduce threats from ice phenomena

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Keywords: water safety, water body, river, dangerous hydrological phenomenon (process), iced phenomenon (process), ice regime, ice-clogging, modeling, monitoring

Abstract. Introduction. The floods caused by ice phenomena are among the "three leaders" of dangerous hydrological phenomena that damage the economy and the environment in Russia. Methods. The methodological basis of the study was: passive experiment, analysis and synthesis, generalizations, methods of mathematical modeling of hydrological and hydraulic processes, multivariate analysis and expert assessments. Results and Discussion. Generalization, analysis and systematization of knowledge about the processes of formation of ice difficulties were carried out. It is shown that under the conditions of climate change and ice regime of water bodies as a result of human economic activity, the methods of forecasting ice phenomena are being transformed, which are mainly based on statistical dependencies established according to the hydrometeorological observations. An updated zoning of the territory of Russia by the genesis of the ice phenomena and types of dangerous hydrological phenomena with recorded material damage is presented. The views on modern methods of monitoring dangerous ice phenomena and the use of its results for timely forecasting, adoption of rules for the use of water resources and preventive measures are expounded, while the consequences of the impact of these phenomena on water bodies are assessed. The modern trends in the development of mathematical modeling of the processes of formation of ice hanging dams and ice jams, the transporting ability of subglacial flows in combination with models of river flow formation and functioning of water management systems are revealed. The prospects for research aimed at developing measures to counter threats to water safety caused by dangerous ice phenomena are determined. Conclusion. The results of qualitative and quantitative analysis can be used to collect information on the consequences of exposure and monitoring of ice hazards. Trends in the development of mathematical modeling of the processes of congestion and anchor ice dam formation, transporting ability of subglacial flows in sections of rivers with engineering structures are associated with a combination of hydrodynamic models, models of river flow formation and the functioning of water management systems. The prospects for research aimed at developing measures to counter threats to water safety caused by dangerous ice phenomena were determined.

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1. Introduction

Water safety is the most important challenge of our time. For the national safety of Russia, the water factor is associated, first of all, with such sources of risks as accidents at hydraulic structures and floods caused by dangerous hydrological phenomenon (DHP). DHP occur in the vast majority of countries of the world [1]. In Russia, the damage from all possible hydrometeorological phenomena is 80–90 % of the total

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damage of a natural environment. At the same time, floods caused by high water, ice jam or ice hanging dam are among the "three leaders" of the DHP, which have a "damaging effect on people, economic sectors and the environment" [1]. In 2020, The Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) recorded 1,000 dangerous hydrometeorological phenomena in Russia (97 phenomena more than in 2019), of which 372 phenomena caused significant damage to critical infrastructure [2]. Such DHPs in each of the subjects of Russia have their own characteristics and different repeatability. The role of each of the possible sources of an emergency accompanied by the occurrence of significant material damage is different and unique both in time and place of origin on the territory of the country [1, 3].

Over the past 25 years, more than 130 ice-clogging floods with recorded material damage have been registered in Russia. The scale of damage varies: from the maximum in the spring of 2001 on the Lena River to the insignificant – in sparsely populated river basins of the Far North. The studies of the processes of ice jam both in natural riverbeds and in regulated sections of rivers show that the development of ice jam and ice hanging dam, as a rule, leads to a decrease channel capacity of the channel and a significant rise in the water level in the river. The annual ice floods on the Sukhona River near Veliky Ustyug [3], the winter flooding on the Volga River in Yaroslavl in 2020 [4], and the formation of congestion in the alignment of the bridge gate across the river are a confirmation of that [5].

Despite the sufficient study of the ice regime of rivers and the processes of ice jams, there are still some urgent problems of the engineering hydrology concerning dangerous ice phenomena, which include:

- the study of the causes and features of their formation;
- the analysis of achievements in the development and application of methods for calculating and forecasting their quantitative characteristics;
- their physical and mathematical modeling;
- monitoring and consequences of their formation both in natural environment and on regulated sections of rivers, including in the presence of engineering structures, to reduce threats to water safety.

The technological complex of engineering hydrology includes monitoring of surface and groundwater, including the observations (with a system for collecting and transmitting information) and the measurements of physical and geographical characteristics; the water resources management technologies; the statistical analysis of hydrological data; the modeling of hydrological (and hydraulic) systems; the hydrological forecasts.

In this study, using the capabilities of the technological complex of engineering hydrology, the following tasks were solved:

1. The search for statistically significant trends in the historical timing of the ice formation and the ice break-up (based on a statistical analysis of the characteristics of the ice regime of the mouth section of the Northern Dvina River in the retrospective period).

2. The classification of the subjects of the Russian Federation by the spectrum of hazardous hydrological and ice phenomena (ice jams and ice hanging dams) with recorded material damage, statistical assessment of the long-term dynamics of these phenomena and the advanced nature of their forecasts in each of the regions.

3. The qualitative and quantitative assessment of the factors that influenced the occurrence of ice jam and the development of winter flooding in the regulated section of the river (based on the results of monitoring the hydrometeorological and hydrological situation in the Volga River basin below the Rybinsk hydroelectric complex).

4. The mathematical modeling of the river flow in the area of the bridge crossing in the conditions of ice jam formation (on a section of the Volga River to assess the flow velocities and slopes of the water surface) followed by an assessment of ice impacts on the temporary transport structure.

2. Materials and Methods

2.1. Area of research

2.1.1. The ice regime of rivers of the north of the European part of Russia

Due to intensive anthropogenesis and climate change, the ice regime of the rivers of Russia, as part of the hydrological regime of the river, underwent significant changes in the XX–XXI centuries. In order to assess the latest changes of the ice regime, it is necessary to retransform information about the ice regime of watercourses in the past.

The continuous data on the ice regime of Russian rivers are available since the first half of the XVIII century. For example, information about the timing of freezing and the complete clearance of the Northern Dvina River from ice has been known since 1734. For the first time, the analysis of long-term observations of the timing of the ice phenomena onset in the basin of this river was performed by K.S. Veselovsky in 1857. In 1868–1869 S.F. Ogorodnikov systematized this information, pointing to the factors affecting the height of water rises, linking the height of the spring flood of the river "... with the rapidity of snow melting, the thickness and strength of the ice, the strength or direction of the wind during the ice breakup of the lower part of the river" [1]. Today, these are generally accepted predictors in models for forecasting the height of ice jams rises in water levels [6]. In the same work, an assumption was made about the possibility of predicting the timing of freezing and ice breakup: "the ice breakup and freezing of rivers are inextricably linked with the air temperature". The research of S.F. Ogorodnikov was developed in the works of M.A. Rykachev (1886)[2] and P.N. Orlov (1915)[3].

The surface air temperature is one of the indicators characterizing the climate change at high latitudes. Compared with the variations in air temperature, the rate of warming in the Arctic in recent decades has exceeded the global and regional warming rates [7]. The increase in the average annual temperature in Arkhangelsk in the last decades of the twentieth century was 0.6 °C, the temperature increase at a rate of 1 °C per 100 years occurred mainly in the cold period of the year [3]. The variability of the near-surface air temperature in the Dvina River Bay of the White Sea was studied for 1915–2015 [8]. It was found that the increase in the average daily air temperature in the spring has shifted to an earlier date, and the decrease in autumn – to a later date; the average rate of change was 10 days in 100 years.

The consequence of the change in the temperature regime was a change in the ice regime of the Northern Dvina River. The dates of freezing have shifted to a later date and the dates of clearing from ice – to the earlier ones [3]. For the lower section of the river for 1880–2004, a statistically significant trend in the timing of the appearance of ice and ice breakup dates was obtained. The freezing came later by 4–5 days, and the ice breakup 2 days earlier. The general trend of shifts in the timing of the appearance of ice and the freezing was revealed throughout the observation period, starting from 1734.

The data on the ice regime of the Northern Dvina River for 1961–2016 were analyzed [9]. For the lower reaches of the river, the dates of freezing shifted by 5 days, the freezing started at higher water levels, which caused an increase in the frequency of ice jams. The timing of cleaning from ice shifted by 4–5 days.

The ice and temperature regimes of the Northern Dvina River according to the reports of the Solombala hydrological post and the Arkhangelsk meteorological station for the period 1914–2013, and historical data for 1733–1855 were studied [10]. A later ice breakup of the river in the period from 1733 to 1855 was explained by the fact that this period belonged to the so-called Little Ice Age. For the dates of the beginning of ice phenomena for 1972–2012, a linear positive trend was obtained [10]. It was noted that the tendencies of deviation of the average air temperature from the norm and changes in the dates of ice formation were unidirectional.

On a 45-kilometer stretch in the delta of the Northern Dvina River almost every spring, ice jams are formed. A lot of historical evidence has been preserved about the spring floods with high water rises and their consequences for Arkhangelsk (high flood of 1621 with ice drift in Kholmogory, water rise of 5.3 m in the spring of 1779, flood of 1811) [11]. Almost annually, in the period from 1900 to 1915 in Arkhangelsk during the spring ice drift, the rise of water was 3-4 meters. To prevent ice jams and related floods in the city since 1915, icebreaking work began to be carried out. From 1922 to 1970, the icebreaking included bombing [12], and since 1954, radiation for ice weakening. Since 1962, directed explosions has became a part of the annual icebreaking works [13]. The early descent of ice into the river mouth has become a powerful anthropogenic factor affecting not only the occurrence of ice jams, but also the course of spring ice phenomena. The ice drift in the Arkhangelsk region began to advance a few days earlier [14]. Over the centuries, the population of the city has grown significantly (from 11 thousand in 1811 to 345 thousand in 2021). The ice regime of the Northern Dvina River is now affected by discharges of warm wastewater from

[1] Trudy Arkhangel'skogo gubernskogo statisticheskogo komiteta za 1867 i 1868 g. [Proceedings of the Arkhangelsk Provincial Statistical Committee for 1867 and 1868]. (rus)

[2] Rykachev, M.A. Vskrytiya i zamerzaniya vod v Rossiyskoy imperii [Breakup and freezing of waters in the Russian Empire]. St. Petersburg: printing house of the Imperial Academy of Sciences. 1886. 309 p. (rus)

[3] Orlov, P.N. Vskrytiye i zamerzaniye reki Severnoy Dviny v g. Arkhangel'ske po dannym za 1734-1915 gg. [Breakup and freezing of the Northern Dvina River in the city of Arkhangelsk according to data for 1734-1915]. Arkhangelsk: Provincial Printing House, 1915. 14 p.

the municipal economy and industrial enterprises. It is very problematic to distinguish the degree of anthropogenic influence and the influence of climate change on the characteristics of the ice regime at the mouth of the Northern Dvina River according to the hydrological data collected later than 1915.

The information basis for long-term analysis of the possible non-stationarity of ice phenomena and the search for statistically significant trends in the historical timing of the ice formation and the ice breakup at the mouth of the Northern Dvina River was the archival information of M.A. Rykachev, supplemented by the data of P.N. Orlov.

2.1.2. Dangerous hydrological and ice phenomena on the territory of Russia

The features of the distribution of DHP, including ice genesis, on the territory of Russia depend primarily on the natural and climatic conditions and characteristics of anthropogenic activity. The various aspects of the impact of DHP on natural and technical systems, flood hazard assessment in Russia and in its subjects are considered, for example, in works of [15, 16]. The use of methods of multidimensional data analysis and GIS technologies in the creation of regional information and cartographic databases on DHP is set out, for example, in the work of [17]. Integrated hydrometeorological modeling for early flood detection is used in foreign practice [18].

The starting material for studies of the long-term dynamics of dangerous hydrological and ice phenomena were Roshydromet data on adverse weather conditions and dangerous hydrometeorological phenomena that caused socio-economic losses in Russia for a 29-year period from 1991 to 2019 [19]. The total data set of DHP includes almost 1900 events.

2.1.3. Factors affecting the occurrence of ice jam and development of winter flooding in the regulated section of the river

The ice jams play an important role in the formation of catastrophic floods on rivers. Features, causes and consequences of the formation of ice jams both in natural and overregulated sections of rivers have been studied for several decades [20, 21, 22]. In the recent years, there have been more studies on regulated rivers as well [5, 23]. The studies showed that ice-hanging dams during the formation of ice covers and ice jams during its destruction mainly develop due to the presence of fractures in the longitudinal profile of the river, increased slopes and flow rates in the river section in combination with fluctuations in the mode of releases to the hydroelectric power station. The conditions for the formation of ice jams in the regulated section of the river differ from the natural conditions of ice jams by the presence of pre-flood discharge of the water level. One of the main reasons (factors) for ice jam is the insufficient flow capacity of the channel (both ice and water) associated with its morphological features [23].

The authors attempted to assess the factors that influenced the occurrence of ice jam and the development of winter flooding on the Volga River below the Rybinsk hydroelectric complex near Yaroslavl in February 2020. For this purpose, they compared this case with a similar situation that occurred in the winter of 2007. The authors used the results of monitoring observations based on operational reports of the Ministry of Emergency Situations of Russia, PJSC RusHydro and Roshydromet. Information from the Federal Agency of Water Resources on the water management situation in the territory of the Upper Volga Basin Water Management and the operating modes of the reservoirs of the Volga-Kama cascade was used as well.

The factor of insufficient throughput of the channel is relatively constant, but in the considered case (2020) on the river section of the Nizhny Novgorod reservoir of the Volga River in the Yaroslavl region, it played a decisive role in the formation of an ice jam.

2.1.4. Factors and methods of modeling river flows in the area of the bridge crossing in the conditions of ice jam formation

For the successful implementation of infrastructure projects in the river basins of Russia, modeling of ice phenomena and the capacity of river channels in the autumn-winter and winter-spring periods, including in the presence of engineering structures on rivers (bridges, crossings, power transmission towers, etc.), is of great importance. An overview of methods of mathematical modeling of ice processes and the experience of their implementation for practical problems is contained, for example, in the papers [23–25].

In [26] issues of dynamics of water flows with ice cover and a set of mathematical models of ice jams and their consequences are considered. The methods of calculation, forecast and comprehensive assessment of the impact of ice jams on the environment were set out in a monograph [27].

Researches [28, 29] are devoted to the creation of a physical model of the ice jammed section of the riverbed. In foreign practice, both one-dimensional mathematical models of ice processes implemented in computer programs RIVICE, RIVJAM, ICEJAM, and two-dimensional ones, for example, CRISSP, are widely used. A comparison of numerical models of river ice jams was made in papers [30, 31].

The object of the study was a new bridge across the Volga River in its middle course during the construction period. The estimated flow rate was assumed to be equal to the construction flow rate with a 10% security of 30,000 m^3/s. The corresponding water levels were determined taking into account the support from the Zhiguli hydroelectric complex, and the calculations were carried out at two levels at the output border, equal to 53.0 m and 54.0 m.

2.2. Research Methodology

The solution of the tasks was established on the methodological approaches based on the fundamental provisions of engineering hydrology and methods of scientific and cognitive activity: empirical (passive experiment) and universal general logical methods (analysis, synthesis, generalization, etc.), as well as methods of mathematical modeling of hydrological and hydraulic processes, mathematical statistics, multidimensional analysis and expert assessments.

The achievements of applied mathematical sciences and the development of the theory of ice processes at the present stage have provided a new way to assess the variability of the ice regime of the mouth of the Northern Dvina River in historical retrospective, which excludes the influence of anthropogenic factors. The methodological basis of the study were multidimensional data analysis and methods of mathematical statistics. Verification of the significance of the trend was carried out on the recommendations of the State Hydrological Institute (SHI, 2010) [32].

The classification of the subjects of Russia by type, number and frequency of occurrence of ice DHP in the development of work of [1] was carried out using the method of multidimensional data analysis – cluster analysis. The regression analysis methods were used to verify the stationarity of long-term DHP series by cluster, region, and type.

The authors generalized the features of ice jam processes in overregulated sections of rivers, and assessed the hydrological situation and ice conditions with an analysis of the causes and consequences of ice jams on the river section of the Gorky reservoir below the Rybinsk hydroelectric complex. The work was carried out as a result of a passive empirical experiment using meteorological, hydrological (on water flows and levels) data and information on ice phenomena on the river. The authors also employed a universal (general logical) method - analysis and synthesis, induction and deduction, generalization. The draft Rules for the Use of Water Resources of the Rybinsk and Gorky Reservoirs on the Volga River were useful for the study.

The assessment of ice impacts on the capacity of the Volga River bed and the temporary bridge crossing during the construction period was carried out by the method of mathematical modeling of the river flow in the area of the bridge crossing in the conditions of ice jam using the Russian software package STREAM 2D CUDA [33]. It was based on the numerical solution of the equations of shallow water in a two-dimensional (planned) formulation and the simplest model (with no consideration of the elastic properties of ice).

3. Results and Discussion

3.1. Statistical analysis of the characteristics of the ice regime in retrospective period

For statistically reliable conclusions about the possible non-stationarity of ice phenomena on the river over a retrospective observation period of more than 180 years (1734–1915), the Northern Dvina was tested for the hydrological homogeneity of the studied characteristics in accordance with the current methodological guidelines of the State Hydrological Institute (SHI, 2010) [32].

A method for estimating the significance of linear regression equations over time was used. If the trend was significantly different from zero, then the hydrological characteristic (including the date of occurrence of the ice event) was non-uniform in time.

The significance of the trend was assessed by comparing the correlation coefficient r of the linear regression equation with a random mean square error calculated by the formula:

$$\sigma_r = (1 - r^2) / \sqrt{n-1}, \quad (1)$$

where n is the number of years of observations. At a 5 % significance level, the condition $r / \sigma_r \geq 2$ must be satisfied, at a 1 % significance level $r / \sigma_r \geq 3$.

Figure 1 shows the factor field of breakup dates from the ice of the Northern Dvina River. The date of the opening of the river corresponded to the first of the dates of the complete clearing of the river from ice. The earliest opening date is April 21, the latest date is June 7. Along the y-axis, the boundaries (Figure 1) of the studied field of opening dates are: April 15 – lower and June 14 – upper. The beginning of the series under consideration corresponds to the 1st year. The domain of definition is taken at 200 years.

The general trend of autopsy dates reversed after 120 years (1860). For verification, 2 periods were considered: observation data from 1734 to 1859 and from 1860 to 1915. The abscissa shows the years (1st – 1734 and 182nd – 1915) of the study series of observations of the opening of the Northern Dvina River. The ice breakup trend equation has the form in the format of numbers: y = -0.038x + 43227. It was obtained as a result of applying the STATISTICA package using the "encoding" of dates (converting the "date" format to the "number" format).

The trend of the ice breakup dates (April 15 to June 14) for the period of 1734–1859 is not statistically significant. The trend for the period of 1860–1915 is statistically significant: the coefficient of determination R2 is greater than 0.1. For the model of paired linear regression, the coefficient of determination is equal to the square of the usual correlation coefficient between y and x at both 5% and 1% (Figure 1).

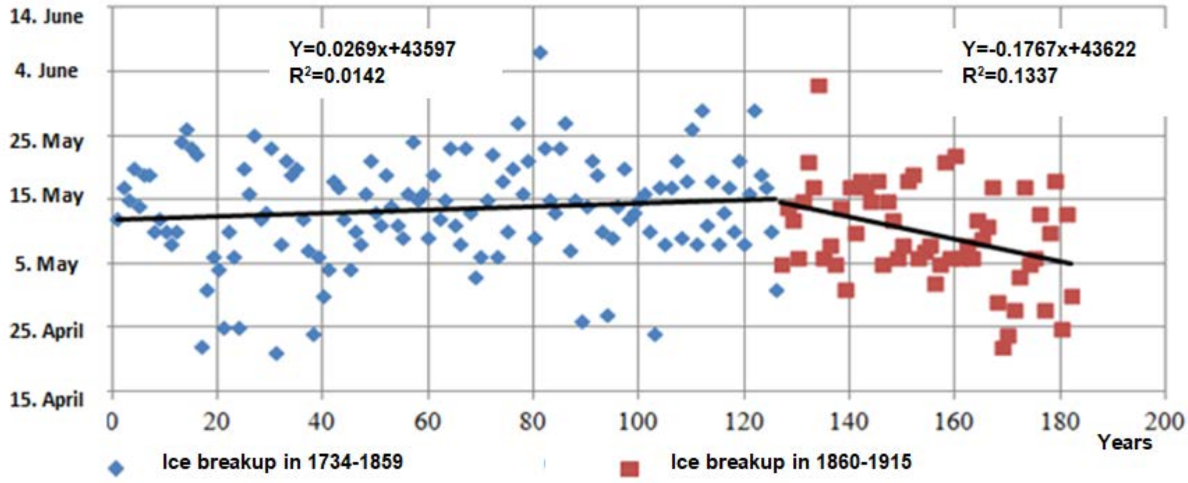


Figure 1. Ice breakup in 1734–1859 (blue) and 1860–1915 (red).

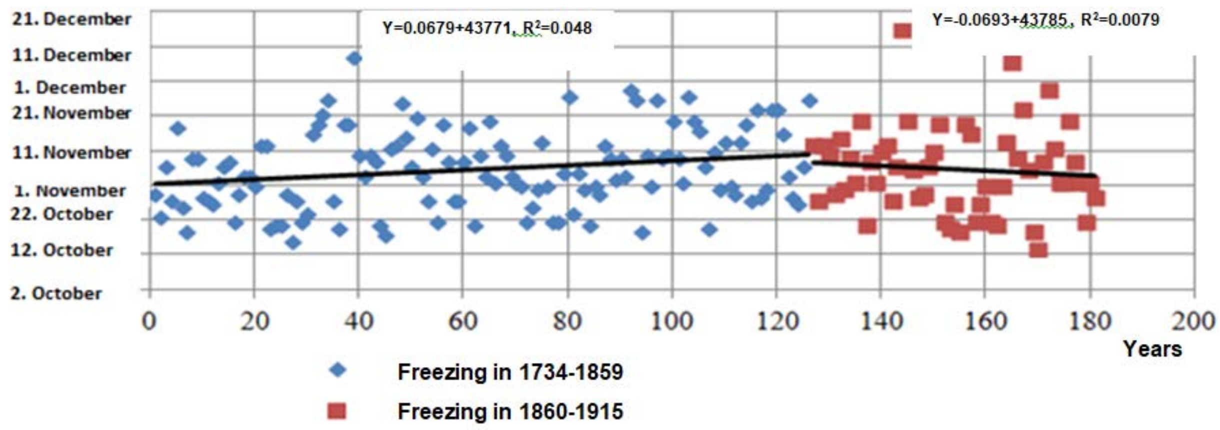


Figure 2. Freezing in 1734–1859 (blue) and 1860–1915 (red).

The trend of dates of river freezing (from October 12 to December 21) for 1734–1859 is statistically significant at the level of 5 %, and at the level of 1 % it is no longer significant. The trend of dates of river freezing in 1860–1915 is not statistically significant (Figure 2). In addition, the shift of the ice breakup dates in 1860–1915 towards earlier dates and the shift of freezing dates in the period 1734-1859 towards later dates were proven.

Analysis of retrospective data for 182 years (from 1734 to 1915) made it possible to exclude the influence of anthropogenic factors on the assessment of the variability of the ice regime on the mouth section of the Northern Dvina River. The identified trends indicated a possible warming of the climate in the northern latitudes. The findings could be useful for analyzing long-term regional and global climate change. Similar conclusions about shifts in the timing of ice breakup and freezing of the rivers of Central Siberia were made based on the results of a retrospective analysis of two-hundred-year observations.

3.2. Classification of the subjects of the Russian Federation by the spectrum of hazardous hydrological and ice phenomena

Floods (33.3%) and high waters (29.8%) caused the most material damage on the territory of Russia out of all the events of the DHP, and cases of recorded damage from ice jams and ice hanging dams amounted to 7.2% and 0.5%, respectively. Descriptive data statistics showed that the maximum number of DHP types found in a particular region (in 2% of the subjects of the Russian Federation) can reach up to six (ice jam and ice hanging dam, low baseflow, high water and flood, mudflow).

For each type of DHP within the territory of Russia, linear trends were built. The temporal homogeneity of the series was checked according to the recommendations of the State Hydrological Institute [32], with the ratio $r/\sigma_r \geq 2$ (r is correlation coefficient; σ_r is root mean square error; n = 29 is the number of years of observations) the trend was recognized as significant at 5 % of the level of significance, with the ratio $r/\sigma_r \geq 3$ trend was recognized as significant at 1 % level of significance [32]. The final conclusion about the significance of the trend or the non-stationarity of the series was made with the same conclusions for 5 %, and for 1 %. The results of assessing the significance of trends for all types of DHP, including ice jams, are shown in Table 1. For the period of 1991–2019, all DHP analyzed with recorded material damage had upward trends, but trends were recognized as statistically insignificant at both 5 % and 1 % significance levels.

Table 1. Significance of linear trends of dangerous hydrological and ice phenomena for 1991–2019.

DHP types	Trend equation	r	σ_r	r/σ_r
Ice jams	y = 0.0546x + 4.4507	0.13	0.19	0.71
All types of dangerous hydrological phenomena	y = 1.0128x + 50.015	0.34	0.17	2.03

Using cluster analysis, the DHP were grouped into 4 typical groups: ice difficulties (ice jam, ice hanging dam, early ice formation), high waters and floods, mudflows, low base flow. The combination of these phenomena is special for each subject of the Russian Federation. Each of the 85 subjects of Russia was assigned to one of nine clusters, depending on the combination of DHP types, which in different years caused material damage to the region [1].

The list of clusters, the combination of DHP types of which includes ice difficulties (ice jams and anchor ice dam, early ice formation), is given below in ranked order:

1. Cluster No. 3 (ice difficulties, high waters): 13 subjects (16 % of all subjects of the Russian Federation),

2. Cluster No. 4 (ice difficulties, high waters, low base flow): 8 subjects (9.9 % of all subjects of the Russian Federation),

3. Cluster No. 1 (ice difficulties, high waters, mudflows, low base flow): 3 subjects (3.7 % of all subjects of the Russian Federation),

4. Cluster No. 2 (ice difficulties, high waters, mudflows): 2 subjects (2.5 % of all subjects of the Russian Federation).

The lists of subjects of the Russian Federation corresponding to each of the clusters No. 3, 4, 1 and 2 are shown in Table 2.

In regions where two or more types of DHP are recorded, the frequency of their occurrence sometimes differs significantly. During the period under review from 1991 to 2019, some subjects of the Russian Federation could bear material losses from high waters, and others could suffer from ice difficulties, etc. Therefore, within clusters No. 3, 4, 1 and 2, a more detailed typing of subjects was carried out according to the share of DHP of each type in their total number.

The division of subjects of the Russian Federation into groups within these clusters was performed by means of cluster analysis in the STATISTICA program using the K-means method and grouping at constant intervals. The results of clustering are shown in Table 2.

Table 2. Clustering of Subjects of the Russian Federation within clusters by DHP frequency of each type.

% DHP case ratio	Subjects of the Russian Federation within each dedicated cluster
Cluster No. 3 (ice difficulties / high waters)	
10% / 90%	Omsk Region, Penza Region, Primorsky Krai, Ulyanovsk Region
30% / 70%	Leningrad Region, Murmansk Oblast, Nenets Autonomous Okrug, Orenburg Oblast, Pskov Oblast, Republic of Tatarstan
47% / 53%	Arkhangelsk Region, Ivanovo Region, Republic of Khakassia
Cluster No. 4 (ice difficulties / high water / low baseflow)	
42% / 57% / 1%	Krasnoyarsk Krai, Republic of Sakha (Yakutia)
10% / 40% / 50%	Novosibirsk Region, Tomsk Oblast
10% / 75% / 15%	Amur Region, Kemerovo Region, Tyumen Region, Khabarovsk Territory
Cluster No. 1 (ice difficulties / high waters / mudflow / low baseflow)	
20% / 75% /2%/ 3%	Altai Republic
24% / 70%/5%/1%	Altai Krai
5% / 50%/35%/10%	Krasnodar Krai
Cluster No. 2 (ice difficulties / high waters / mudflows)	
25% / 70% / 5%	Zabaykalsky Krai (Trans-Baikal Territory)
10% / 70% / 20%	Republic of Dagestan

Within each cluster, depending on the share of DHP of each type, the subjects of the Russian Federation were also divided into groups. For example, cluster No. 3 unites regions for which material damage was caused by such types of DHP as ice difficulties and high waters. In the Omsk, Penza and Ulyanovsk regions, as well as the Primorsky Krai, on average, only 10% of all cases of the recorded material damage were caused by ice difficulties, the remaining 90% of cases were due to high waters and floods. In addition, in cluster No. 4, which unites other subjects of the Russian Federation, material damage was caused by such types of DHP as ice difficulties, high waters and low baseflow. For example, in the Novosibirsk and Tomsk regions, on average, 10% of all cases of the recorded material damage was caused by ice difficulties, 40% were due to high waters and floods, and 50% were due to low baseflow. In the Krasnoyarsk Territory and the Republic of Sakha (Yakutia), an average of 42% of all cases of recorded material damage was caused by ice difficulties, 57% of cases were freshets and floods, and the remaining 1% of cases were caused by low baseflow.

The use of cluster analysis methods made it possible to zone the territory of Russia according to the predominant types of DHP (including ice) and to assess the degree of exposure of the subjects of the Russian Federation to their impact. The information obtained makes it possible to assess the territorial risks caused by DHP and to timely identify negative processes. The possible manifestation of that may affect the occurrence and development of emergency situations in water bodies and adjacent territories. Floods, freshets and ice difficulties (congestion and anchor ice dam) cause material damage in a significant part of the subjects of the Russian Federation. Therefore, the organization of monitoring of these DHP on the territory of Russia is a priority.

3.3. Assessment of the factors that influenced the occurrence of ice jam and the development of winter flooding in the regulated section of the river

On the longitudinal profile (Figure 3) of the Nizhny Novgorod Reservoir [4], a 50-kilometer "rapid" section of the channel near Nekrasovskoye village on the river section from Yaroslavl to Kostroma is visible. In addition, it is on this section of the Volga River that large morphometric obstacles are located: several islands, narrowings and turns of the channel. It is obvious that these morphometric barriers have led to the restriction of the living section and the formation of slush in some areas in this part of the reservoir. The combination of unfavorable morphological conditions, the alternation of strong thaws and significant cold snaps, unstable ice and short-term winter ice drift in an exceptionally ice jams area in the zone of wedging the water level of the Nizhny Novgorod Reservoir in the area of Mininsky Island have led to the formation of an ice jam above Nekrasovskoye village. The formation of ice jam caused a significant narrowing of the live section of the flow, but at the same time the decrease in capacity in this section of the channel (taking into account the additional rise in the water level above the ice jam) did not exceed 30–40%, and an ice survey of ice jam was not carried out.

A decisive role in the formation of ice jams in the river section of the Nizhny Novgorod Reservoir both in 2020 and in 2007 was played by the factor of insufficient ice and water capacity of the channel associated with the morphological features of the Volga River section. The time of formation of ice jams both in February 2020 and in January 2007 clearly coincided with the periods of significant fluctuations of tail-water volume at the Rybinsk hydroelectric complex with their overall significant growth. In both cases, during the formation of ice jams, the water level at the dam of the hydroelectric complex of the Nizhny Novgorod Reservoir was discharged by more than 0.3–0.35 m due to a corresponding increase in discharge costs at the Nizhny Novgorod hydroelectric complex.

This once again confirms the extremely negative impact of the water level in the reservoir before the flood on the conditions and the possibility of ice jams on the regulated section of the river above the hydraulic complexes.

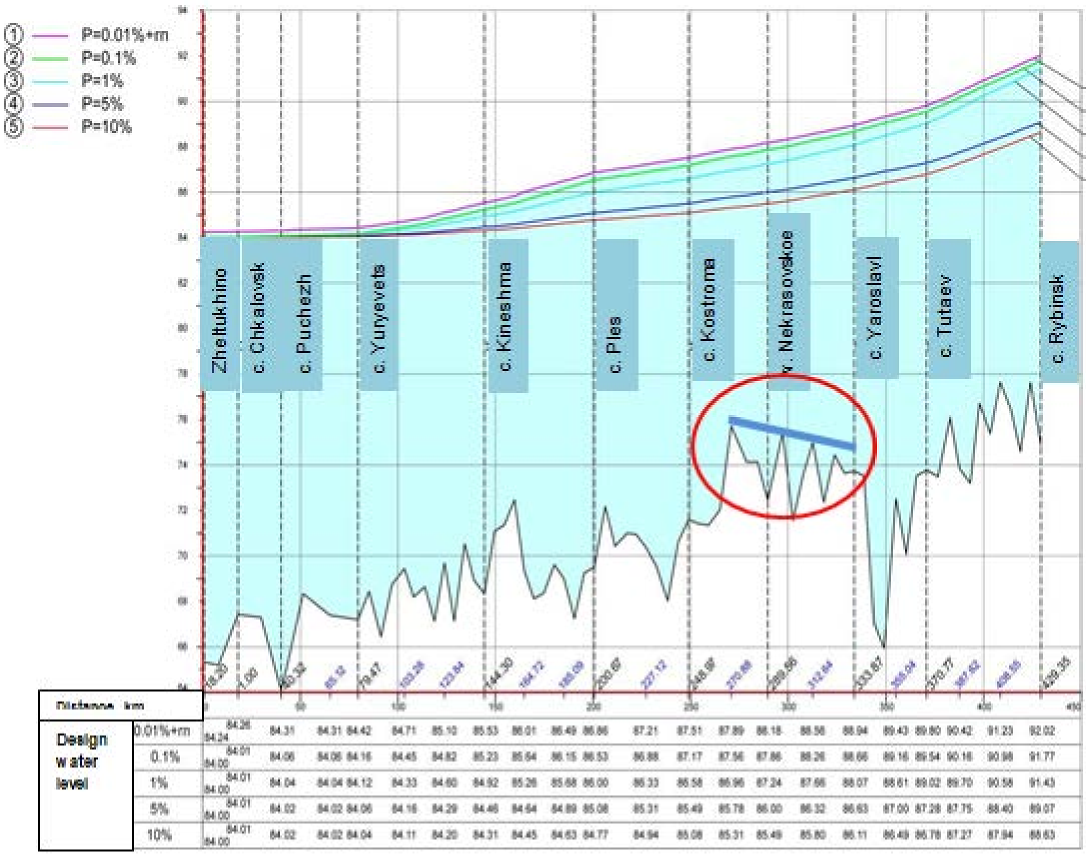


Figure 3. Calculated curves of the free surface of the Nizhny Novgorod Reservoir on a congestion-prone section of the Volga River 1, 2, 3, 4, 5 – water levels (m) for years of different probability of exceeding [4].

The magnitude of the maximum rise in ice dam levels in the Volga River near Yaroslavl in 2020 exceeded the maximum of 2007 by almost 1 m with even slightly smaller fluctuations in discharges from the Rybinsk reservoir. Under very similar weather and hydro meteorological conditions, in both cases, the main difference was the "lower background" of water levels in the upper stream near the dam of the Nizhny Novgorod hydroelectric complex (in 2020 in January-February they were 0.8 m lower than in 2007). Therefore, when establishing the operating modes of reservoirs, special account should be taken of the emerging water management and hydro meteorological situation, taking into account the analysis of observations of hazardous hydrological phenomena on the water body. The results of the study were used to substantiate the modes of operation of the reservoirs of the Volga-Kama cascade of hydraulic complexes and the development of a new edition of the regulations for the use of water resources of reservoirs.

3.4. Modeling of river flow in the bridge area under conditions of ice jam formation

The hydrodynamics of the streams was taken into account by additional friction on the inner surface of the ice cover. For tangential stresses on a free surface, a quadratic dependence on the average depth of the flow velocity with Manning roughness coefficients n was assumed. At the same time, the influence of wind was not taken into account, since the free surface of the water was shielded by ice. The problem of the vertical velocity profile in the subglacial stream was not considered, since it is not significant for determining water levels in ice jam floods.

Full-scale measurements of real currents showed that additional roughness coefficients from the presence of ice on the surface of the flow have values from 0.02−0.03 for the average winter period to 0.03−0.06 or more in the presence of ice jam during the flood period [34, 35]. In the calculations, the total roughness coefficient for the area with ice jam was taken to be equal to 0.05.

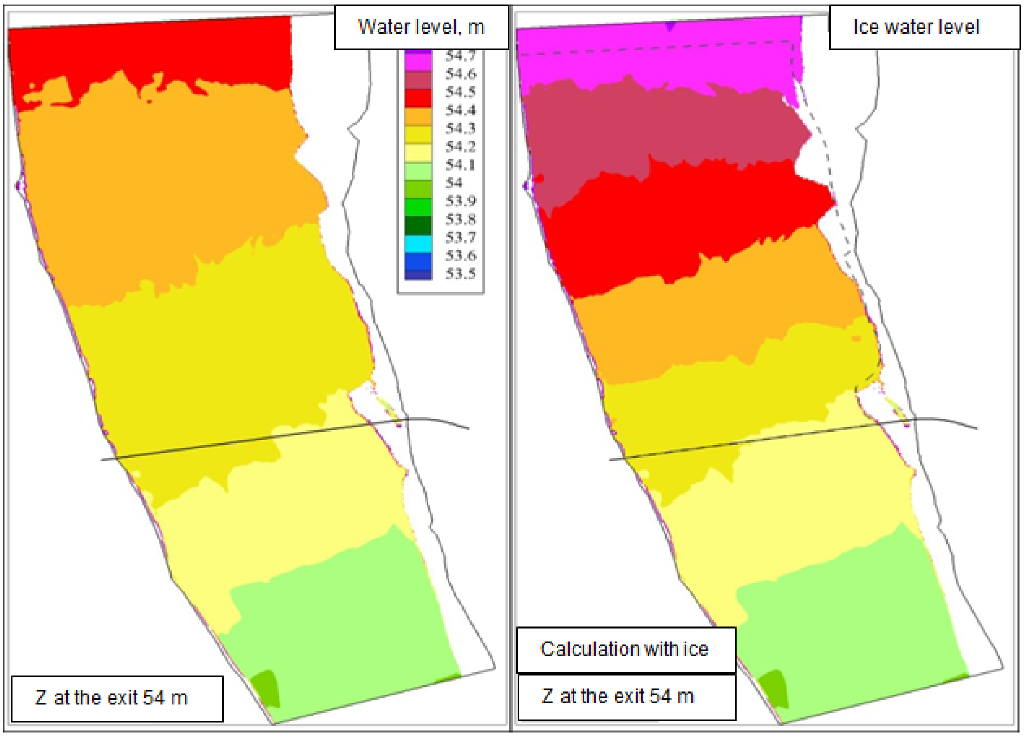
A digital elevation model (DEM) of the Volga River bed above and below the gate of the bridge crossing was constructed (Figure 4). Calculations of water levels and flow rates in the conditions of the ice jam formed along the entire width of the channel with an ice thickness of 0.73 m (with the probability of exceeding 10% and obtained from field measurements in early March 2021) were performed by means of the STREAM 2D CUDA software package development of NPP Aquarius Analytic LLC [33]. For numerical simulation in the computational domain, a hybrid grid of a triangular-quadrangular structure (63 thousand cells) was used.

In the calculations, the ice jam was located above the gate of the bridge crossing the entire width of the river at a distance of 6 km upstream. According to hydrological surveys, at water flows of 29800 m^3/s and 30200 m^3/s, the water levels in the gate of the bridge crossing were equal to 54.16 m and 54.34 m (during the ice age), respectively. At the same time, the slope of the water surface in the area above the bridge without ice is 3 cm/km (I = 0.00003), and taking into account the stable ice (ice jam is located above the bridge) – 6.7 cm/km (I = 0.000067), i.e. increases by more than 2 times. The depth of the flow along the line of the main fairway at such levels reaches 18–19 m, and in the shallow water zone is 5–6 m Fig.4.

The calculations taking into account ice phenomena for the conditions of spring 2021 have shown that the temporary structures that existed at that time practically do not affect the hydrodynamic characteristics of the flow and the ice itself cannot have a strong negative impact on them.

Forecast calculations of ice phenomena for the conditions of spring 2022, when the temporary bridge will be fully operational, can lead to a long ice jam (up to 10 km long). However, the ice cutters provided for the temporary bridge, according to the assessment, should cope with the regulatory load. With an ice jam length of 7.5 km, they should start cutting the ice floes.

The ice load on the supports of a permanent bridge during the period of the temporary bridge preservation can reach 60 Tf per support due to the effect of ice jam, in addition, a shock effect from floating single ice floes is possible (the strongest is in the deep-water part of the fairway, where speed reaches 2 m/s). These issues require further special studies and observations.



a) b)

Figure 4. Comparison of water levels calculated at Q=30000 m^3/s (a – without ice, b – with ice) with the water level at the output boundary of 54 m (dash line – ice boundary, solid line – gate of the bridge crossing).

4. Conclusion

In the context of climate change and the ice regime of water bodies as a result of human economic activity, the methods of forecasting ice phenomena are being transformed, which are mainly based on statistical dependencies established according to hydro meteorological observations.

The results of continuous monitoring of ice and hydrological regimes are important for timely forecasting, taking preventive measures and assessing the consequences of the impact of ice hazards on water bodies.

Russian territories were clustered by the genesis of ice phenomena and types of dangerous hydrological processes with recorded material damage, obtained using the cluster analysis method. Ensuring counteraction to technogenic and natural threats on water bodies, the developed information resource can be used in determining regional lists and criteria for dangerous ice hydrological phenomena, collecting information about the threat, possible consequences and monitoring of such processes. The results of qualitative and quantitative analysis can be used to collect information on the consequences of exposure and monitoring of ice hazards, as well as to provide public authorities and other organizations with factual and predictive data on hydrological hazards in the whole country and on the territory of the subjects of the Russian Federation. In addition, the results of the study can be used to substantiate the modes of operation of reservoirs of hydraulic complexes (cascades of hydraulic systems) and the development of regulations for the use of water resources.

Modern trends in the development of mathematical modeling of the processes of ice jam formation, transporting ability of sub glacial flows in sections of rivers with engineering structures are associated with a combination of hydrodynamic models, models of river flow formation and the functioning of water management systems.

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