ISSN 0097-8078, Water Resources, 2007, Vol. 34, No. 2, pp. 123–131. © Pleiades Publishing, Ltd., 2007.
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Specific Features of Ice Regime in Rivers of the Northern Dvina Basin

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Received February 16, 2006

Abstract—Variations in the characteristics of ice regime of rivers in the Northern Dvina basin over the last 125 years are analyzed. For the Northern Dvina lower course, potential changes in the dates of the appearance of floating ice and the breakup due to expected changes in the air temperature and the rate of streamflow in rivers are assessed. Special attention is paid to the factors that affect the formation of ice jams and their spatial and temporal variability. The prognostic relationship for the maximum ice-jam stage in the Sukhona River near the town of Velikii Ustyug is presented as an example.

DOI: 10.1134/S0097807807020029

INTRODUCTION

Active involvement of river basins' resources into the economical sphere entails a complex of adverse consequences that cause hazardous changes in the extreme water discharges, the direction and intensity of channel deformations, water quality, the state of aquatic ecosystems, and the conditions of economic activity of population. Crucial environmental situations in rivers of the Northern Dvina basin arise during spring floods or overflows caused by ice jams. Therefore, the investigation of different phases of ice regime (freezing, freeze-up, and breakup) that directly affect the regime of spring flood and the formation of ice jams is an important scientific and practical problem. The consideration of these issues is the goal of this paper.

Stationary observations of ice phenomena on rivers in the Northern Dvina basin were initiated simultaneously with those of level regime. The earliest observations go back to 1876–1885 (on the Northern Dvina, Sukhona, and Vychegda rivers). The many-year observational data allow us to comprehensively assess the spatial and temporal variability in the ice regime characteristics.

PHASES OF RIVER ICE REGIME IN THE NORTHERN DVINA BASIN

The rivers of the Northern Dvina basin feature a steady freeze-up. The exceptions are certain reaches of water streams having rapids and karst and also some rivers that outflow from lakes; here the freeze-up is unsteady or absent at all [9].

The characteristics of ice regime are mainly governed by climatic factors but also depend on morphologic and hydraulic features of the channel and flow. For example, on small rivers (the Tiksna, Ema, Enanga), the process of freezing proceeds by way of closure of thin ice extending from the banks. On medium rivers (the Vychegda), this period is characterized by the formation of young shore ice and floes and the ice drift. The ice cover develops along the river due to the ice dams forming in the sites of decreased ice conveyance of a flow. On large and medium rivers (the Northern Dvina), particularly in the high-water years and under unsteady weather conditions, the process of freezing is accompanied with the formation of sludge and its movement downstream. Ice jams form in the reaches with increased slopes. Upstream of the sites of their formation, river water outflows onto ice and forms sludge or flood icing. However, such rises in water level are of short duration and in the overwhelming majority of rivers, they are 100 cm. For example, the rise of water level caused by an ice jam near Medvedka Village (Northern Dvina) averages 140 cm and that near the Syktyvkar Town (Vychegda) averages 120 cm.

The freezing period on large rivers has some special features. The Northern Dvina lower course freezes up 8–10 days earlier than other reaches, whereas the Vychegda lower course freezes up later than its upper course where the climate is more continental. The dates of freeze-up change along the Sukhona River, depending on the water surface slopes. Relatively early dates of freeze-up on the Sukhona reach near Ust-Pinega Village are due to the inflow of the Pinega's cold water; in the Sukhona middle course, these dates are controlled by the effect of rifts.

The average duration of the freeze-up period in the Northern Dvina basin varies from 144 to 185 days. On the Sukhona, this period lasts for 144–150 days in the reaches with rapids and up to 185 days in the northeastern part of the basin.

The spring processes of breakup begin with snow melting on ice. Under the effect of melt water coming from the watershed, ice cracks and near-bank water margins appear in the ice cover; individual floes flow up; advances of ice begin and then transform into ice drift; ice jams are also common. Thus, the process of breakup is controlled by both the thermal and mechanical factors.

On the Northern Dvina, the ice breaks first downstream of the influx of the Sukhona, Yug (Velikii Ustyug Town), and Vaga (Bereznik Village). The breakup on the Sukhona and Vychegda rivers occurs very rapidly and averages three days. On the Northern Dvina, this period varies from 8 to 25 days in different years; in extreme cases, the breakup lasts for mere two days. Thus, the breakup process on the Northern Dvina is controlled by the breakup on its tributaries, i. e., by the energy of flood wave.

The breakup in the Northern Dvina mouth area has some peculiarities. The breakup and ice drift in the delta branches begin in their heads, simultaneously with the breakup of the river near Arkhangelsk. First, icebreakers break the ice cover in the Maimaksa navigable branch. The breakup on branches is often accompanied by ice jams. The natural process is disturbed by the artificial ice destruction, discharges of warm (from heat electric power plants) and waste (from industrial enterprises) waters, and by the pollution of ice surface. In recent years, owing to the effect of the town, the ice drift in the region of Arkhangelsk began several days earlier than before [8].

The earliest breakup is characteristic of effluent and karst rivers. For example, the Emtsa River near Sel'tso Settlement usually becomes free of ice without ice drift (ice melts on the spot) 10–15 days earlier in spring than the nearest non-karst rivers. Within some reaches, karst rivers do not freeze at all.

According to the specific features of ice regime, the Northern Dvina basin can be divided into three large regions: eastern—the basin of the Vychegda River; southern—the basin of the Sukhona and Yug rivers; central—the Northern Dvina and its tributaries in the middle and lower courses.

Eastern region. The general direction of water flow in the Vychegda basin is from northeast to southwest. The freezing of the basin is accompanied with the formation and dense drifts of sludge and ice jams (at the majority of gauges, in 100% of cases). Owing to the Vychegda's sub-latitudinal flow, the duration of the autumn ice drift features almost no changes along the river. The breakup develops very rapidly, within three days on average. Ice jams are very rare here. The location of this region in the eastern part of the Northern Dvina basin determines continental climatic conditions here, which manifest themselves in a prolonged period with ice phenomena (up to 220 days).

Southern region. The Sukhona basin features the latitudinal (from west to east) direction of water flow. The ice phenomena begin on October 30–November 5. Specific features of their formation are typical of the Sukhona outflow from Lake Kubenskoe and the rapids in its middle course. The duration of the autumn ice (sludge) drift on the Sukhona River increases up to 50–60 days. The breakup develops virtually simultaneously along the entire river length (during three days on average). The duration of freeze-up is 144–150 days.

Central region. The general direction of the flow in this part of the Northern Dvina basin is from south to north. The ice phenomena begin on October 20–25 in the northern part of the region and on October 26–30 in the rest of it. The Northern Dvina mouth area freezes up from both the offing and shallow delta branches and from the river. The principal factor that controls the breakup is the flood wave energy on the main river and its tributaries. The breakup is accompanied with ice jams at the channel bends and narrow spots. On some rivers (the Emtsa, Sheleksa) the ice regime is subject to the effect of karst. The breakup on the karst rivers occurs 10–15 days earlier; some reaches of these rivers do not freeze up over the whole cold period.

TEMPORAL VARIABILITY OF ICE REGIME CHARACTERISTICS

To assess changes in the ice regime of rivers in the Northern Dvina basin, the authors analyzed the maps (Figs. 1, 2) of the mean dates of the start of freeze-up and breakup for the periods of 1881–1937 (maps from [2]) and 1938–1988 (maps constructed by the authors).

The freezing of rivers begins in the northern and eastern parts of the Northern Dvina basin (on November 1–10), further it spreads to the central (November 10–15) and southern parts (November 15–28), including the Sukhona middle course, which is full of rapids. Over 1881–1988, the situation in the basin changed only slightly, except for that in the Vychegda basin, where the river freezing in the second period began 2–3 days earlier than in the first period (Fig. 2).

The breakup begins in the southwestern part of the Northern Dvina basin: on April 20 (on average), on the rapid-containing Sukhona reaches and on the rivers of the Yug and Vaga basins; on April 20–25, on the rest of the Sukhona; on April 25–30, on the Northern Dvina itself and in the Vychegda lower course; the process of breakup terminates on April 30– May 4 in the northeast of the Northern Dvina basin. The situation did not virtually change over more than 100 years (1881–1988), (Fig. 2).

The available series of observations of the ice regime characteristics over more than 100 years made it possible to study in detail the temporal variability of ice phenomena in the Northern Dvina basin.

During the last decades of the 20th century, climate changes and their consequences have attracted considerable interest. As is known, the global air temperature near the Earth's surface increased by 0.6 ± 0.2°C. In the

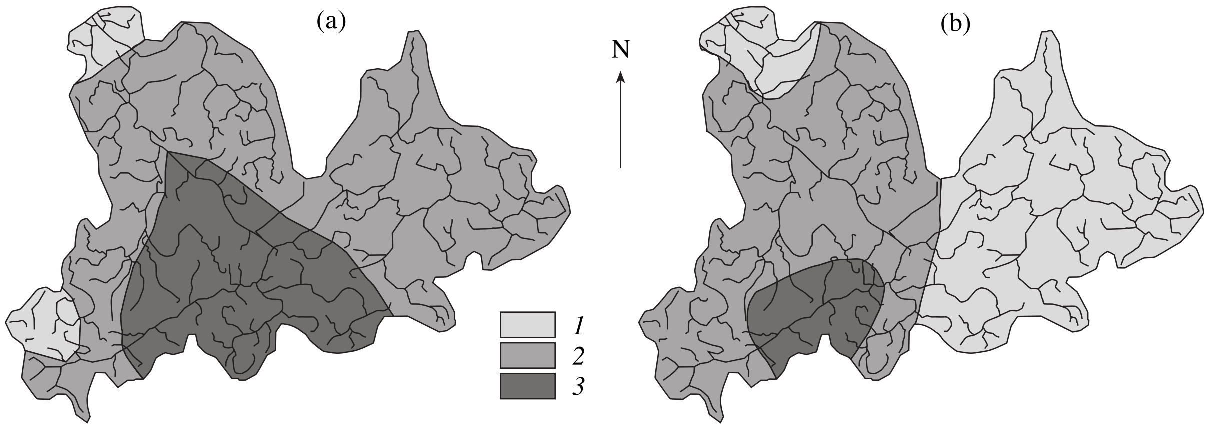

Fig. 1. Dates of the start of freeze-up on rivers in the Northern Dvina basin for (a) 1881–1938 [2] and (b)1938–1988. (*1*) Before November 10, (*2*) from 10 to 15, and (*3*) after November 15.

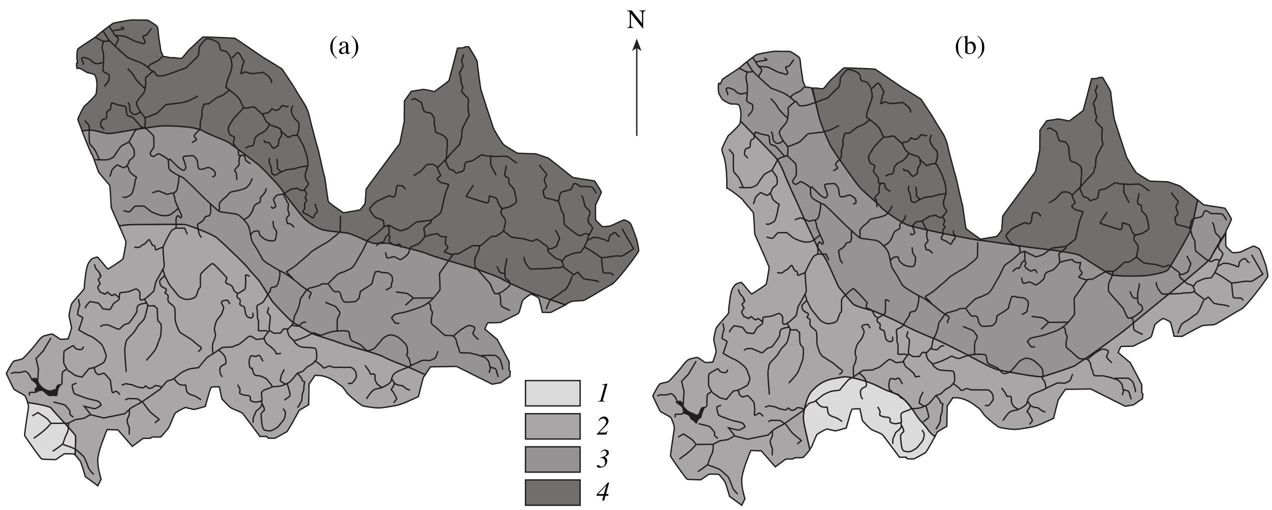

Fig. 2. Dates of breakup on rivers in the Northern Dvina basin for (a) 1881–1938 [2] and (b)1938–1988. (*1*) Before April 20, (*2*) from 20 to 25, (*3*) from 25 to 30, (*4*) after April 30.

northern part of European Russia, the mean annual air temperature over this period increased by 0.6°C (Arkhangelsk) mostly due to a temperature increase in the cold period of the year (1.0°C/100 yr) and to a lesser degree in the transition periods.

The global warming manifests itself in a number of natural phenomena, including the dates of formation and destruction of ice cover on rivers. The graphs of the anomalies of dates of ice appearance and breakup in the Northern Dvina lower course over the last 120 years reflect the general moderation of ice regime: the linear trend in the dates of ice appearance and breakup is 4.6 and 1.2 days per 100 years, respectively. Analysis of the difference–integral curves for these values and other methods of temporal analysis allowed us to identify the periods with the predominance of positive and negative anomalies. After the 1882–1914 period of relatively early dates of ice appearance, the air temperature in the autumn period preceding the freeze-up began to grow, thus leading to a later appearance of ice on rivers. The deviation of the date of ice appearance from the norm for 1961–1990 was three days (over the 1914–1990 period); the same rate of changes in the dates has retained in the recent 15 years. The long-term variability of the anomalies of dates of ice appearance faithfully copies the long-term course of air temperature in autumn, the coefficient of correlation between the anomalies of dates of ice formation and the mean air temperature in October (Arkhangelsk) equaling 0.7. Another factor controlling the ice regime on rivers is the rate of streamflow in the period preceding the freeze-up. For the Northern Dvina, the coefficient of correlation between the anomalies of the dates of ice appearance and the water discharges in this period is 0.46. The coefficient of multiple correlation between

Table 1. Deviation of the date of ice appearance, days, from the mean value for 1961–1990 in the Northern Dvina lower course at changes in the mean monthly air temperature in October Δt, °C and the water runoff ΔQ over the period preceding the freeze-up

Δt	ΔQ, %			
	–25	0	25	50
0.5	–1.5	0	1.5	3.0
1.0	0	1.5	3.0	4.5
1.5	1.0	3.0	4.5	6.0
2.0	1.5	4.5	6.0	7.5

Table 2. Deviation of the date of breakup, days, from the mean value for 1961–1990 in the Northern Dvina lower course at changes in the mean monthly air temperature in April Δt, °C and the water runoff ΔQ over the period preceding the breakup

Δt	ΔQ, %			
	–25	0	25	50
0.5	0.7	–0.3	–1.5	–2.5
1.0	0	–1.0	–2.0	–3.0
1.5	–0.5	–1.6	–2.5	–3.5
2.0	–1.0	–2.0	–3.0	–4.0

the anomalies of dates and the two above factors is 0.79. Note that the correlation between the air temperature and the rate of streamflow in autumn is virtually absent—the coefficient of pair correlation between them is 0.12. Unlike the air temperature, the rate of the Northern Dvina streamflow in autumn does not feature any pronounced trend. The long-term course of the dates of breakup on the Northern Dvina is more complicated. The air temperatures in spring were relatively low in 1890–1900 and 1938–1972 and increased in 1901–1922 and 1973–2004. In accordance with this, the dates of breakup in the Northern Dvina lower course were relatively late in the former two periods and early in the latter two periods. Similar to the dates of ice appearance, those of breakup depend on two factors—the air temperature and the rate of streamflow. In the case of breakup, the coefficients of correlation between the series of the anomalies in the dates and the mean air temperature for April $r = -0.74$, between the anomalies of dates and the Northern Dvina runoff (Ust-Pinega gage) $r = -0.77$, and the multiple coefficient of correlation $r = 0.82$. The potential changes in the dates of ice appearance and breakup on the Northern Dvina downstream of the settlement of Abramkovo were estimated by the equation of multiple correlation between the dates of ice phenomena and the rate of river streamflow for the appropriate month. The results of calculations are presented in Tables 1 and 2. Changes in the dates of ice appearance may become significant if the mean monthly air temperature increases on average by 1°C (the mean annual temperature, by ~2°C) and the rate of streamflow in autumn by ~25%. Under the same conditions, the dates of breakup will change to a lesser degree than those of ice appearance: they will be only two days earlier. Thus, even significant climatic changes in the nearest 20–30 years should not lead to considerable changes in the dates of ice phenomena in the Northern Dvina lower course.

It is of interest that the value of the linear trend in the dates of the start of freeze-up on the Sukhona near Velikii Ustyug town is mere 1 day/100 yr and this trend is absent in the Sukhona upper course (Tot'ma Town). The situation with the dates of breakup is reverse; the changes in the dates grow upstream the Northern Dvina from 1.2 days per 100 years in its lower course to 3.5 days on the Sukhona near Velikii Ustyug and 4 days on the Sukhona near Tot'ma. Thus, the dates of ice appearance changed most in the lowest reach of the Northern Dvina, whereas the dates of breakup, in its upper and middle parts (Sukhona R.). The existence of a monotonous (increasing or decreasing) trend in the series under study was checked using Spearman's non-parametric test [11] based on the estimate of the coefficient of correlation r_S between the ranks of the terms in the series and the numbers of the relevant years. According to the results obtained, the series of many-year variations in the dates of breakup for the Sukhona near Tot'ma and Velikii Ustyug feature a downtrend and the series of ice appearance on the Northern Dvina downstream of Abramkovo Settlement features an uptrend. The changes in the dates of ice phenomena on small and medium rivers in the Northern Dvina basin are overall insignificant, whereas those on large rivers (the Sukhona and Northern Dvina) demonstrate a general tendency toward milder ice regime, which manifests itself in shifts in the dates of ice appearance and breakup.

The above general tendency toward shifts in the dates of ice appearance, start of freeze-up, and breakup has been characteristic of the whole 300-year period of observations of ice phenomena in the Northern Dvina mouth (Archangelsk).

FORMATION OF ICE JAMS ON RIVERS IN THE NORTHERN DVINA BASIN

An important feature of river ice regime in the Northern Dvina basin is the formation of ice jams. It is characteristic of the initial stage of breakup, when ice is not completely destroyed, floating ice consists of many large ice floes, which provoke the formation of ice jams, and the energy of flood wave is insufficient for their destruction. Sometimes, ice jams appear simultaneously with the start of breakup and are often a consequence of the non-synchronous flood waves on the main river and its tributaries (for example, on the Northern Dvina near Bereznik Village). The sites of ice

Fig. 3. Recurrence of ice jams in the Northern Dvina basin, %. (*1*) up to 40, (*2*) from 41 to 60, (*3*) from 61 to 80, (*4*) >80.

jam formation can vary from year to year, though on large rivers they are mostly stationary. Ice jams are regular at the sites of sharp bends of the Northern Dvina near Orlentsy Village and the Sukhona near Opoki Village and at the site of the Northern Dvina dividing into numerous delta branches.

There are three groups of factors that control the ice jam formation [12]:

morphologic factors including the type of the river reach, the form of the river valley cross-section, and the channel formations that reduce its conveyance capacity;

hydrologic factors including the rate of changes in water level, the form of hydrograph (one or two flood waves during the breakup; the phase synchronism of breakup, ice jam formation, and maximum water flow); and

structural factors including the structure of ice-jam nucleus (the general structure of ice-jam accumulation); the location of the edge of ice cover, ice dam, the accumulation of ice floes, the edge of the ice-jam accumulation that formed earlier, and bottom ice in the zone of formation.

There are 114 ice-jam reaches in the Northern Dvina basin, 60 of which are or were subjects of hydrologic observations (Fig. 3). The frequency of ice jams on individual reaches is up to 86%. The ice-jam level rises vary from 80 cm (the Verkhnyaya Toima, Yarenga, and Ezhuga rivers) to 100–150 cm or more (the Northern Dvina, Sukhona, Pinega rivers, and others).

On the Northern Dvina [9], ice jams usually form within the reaches near Velikii Ustyug and Kotlas towns, Dvinskii Bereznik Settlement, Orlentsy Village, and Kholmogory Settlement. The formation of ice jams near the former two towns is due to a drastic decrease in the water surface slope and the presence of islands and sharp bends of the channel or primary bank; ice jams near Orlentsy form due to an extremely abrupt turn of the river and narrowing of the channel; ice jams near Kholmogory are due to the division of the river into numerous shallow branches and the presence of several sharp turns of the main channel (during its advances in this place, ice abuts against the primary bank); in the river delta, ice jams are due to a decrease in the water surface slope and the flood wave energy because of the channel braiding into several wide and shallow branches. The breakup on the Minor Northern Dvina begins in its head; the ice that is carried away from the upper reaches strikes against the immobile ice near the Vychegda mouth and blocks up the narrowed river reach (between Pustoi Isl. and the right bank) down to the bottom, forming an ice jam, which extends 10–12 km upstream. The effective cross-section becomes filled in with compacted ice down to a depth of 4–5 m. The height of hummocks reaches 6 m in some years. The breakup on the Vychegda River always occurs later and does not affect the ice jam formation on the Minor Northern Dvina [7]. Ice jams near Dvinskii Bereznik Settlements form due to other causes. Here, ice jams generally occur in the years when the flood wave in the Vaga River leaves far behind that in the Sukhona (the Vaga flood wave energy is not enough to break up the ice cover within a considerable reach of the Northern Dvina). Ice jams also form in the Northern Dvina mouth, near Arkhangelsk Town. After 1915, the number of ice jams in the delta sharply decreased due to the ice-breaking works in the Maimaksa navigable branch.

The breakup in other delta branches is often accompanied by strong ice jams in the upper parts of the branches [8].

Ice jams on the Sukhona form generally near the islands of Elovets, Osovoi, and Dedov and also at the sharp river bends near the villages of Dvinitsy, Motyri, Chernovskie, Selizhe, and Opoki; they are also not infrequent in the river mouth near Velikii Ustyug Town. Ice jams in river mouths are usually a rear continuation of the above-mentioned ice jams on the Northern Dvina; sometimes the ice jam head is located on the Sukhona, upstream of its confluence with the Yug. Such situation is observed when the Yug breaks up simultaneously or somewhat earlier than the Sukhona, creates a strong backwater effect within the mouth reach, and hinders the advance of ice from the Sukhona into the Northern Dvina [1].

Ice jams form permanently on the Yug, at the site of a sharp river bend near Strelka Village, 12 km upstream from the mouth, on the Vychegda near Syktyvkar Town, on the Vaga near Shenkursk Town, and on the Pinega near Kuzomen Settlement. The length of large ice jams is several kilometers (up to 20 km on large rivers). The duration of their existence varies from several hours to 3–5 days. At the sites of river channel braiding (Northern Dvina mouth reach), ice jams generally bypass ice accumulation in the main channel, which exist within 5–10 days or more after the ice breaks from the site of braiding.

The process of breakup in the Northern Dvina basin is largely governed by the rate of rivers' streamflow and the meteorological conditions. The following regularities of the distribution of ice jams in the basin have been identified. In the warm (in terms of the sum of the mean monthly air temperatures for winter, i.e., November–March period), high-water (in terms of the maximum water discharge in the Northern Dvina lower course near Ust-Pinega Settlement) and medium-water years, ice jams form in almost all ice-jam–favorable reaches in both upper and lower courses of rivers (1962, 1983, and 1955). In warm, low-water years, ice jams form in the Sukhona lower course and the Vaga upper course. These ice jams retard the process of breakup and enable the ice drift in the Northern Dvina to proceed free of ice jams. In cold years, ice jams form uniformly, i. e., in the lower and upper courses, perhaps due to a large amount of ice in the rivers. In cold years, ice jams are less frequent than in warm years, when the breakup develops relatively quickly (<10 days) and ice jams occur along the whole length of rivers. In low-water years, ice jams are rather often observed in the Vychegda basin.

The principal factors of ice jam formation are [10] the types of winter (severe or mild) and spring (rapid or slow); the retard of breakup because of a thick ice cover; the presence of a barrier for water flow due to the morphologic features of the channel; the rate of flood rise.

The likelihood of a strong ice jam in the river is determined by the following characteristics [3]: double or triple ice drift in autumn and a high water level in the period of river freezing; a large amount of ice caused by a high freezing level at which a considerable river area is covered with ice, the channel being filled with sludge (50–80% of the cross-section area), and the thickness of ice cover by the start of breakup >0.7 m; the ratio of the ice thickness in the reach of ice concentration to that at the site of ice jam formation <0.5; a high strength of ice before the breakup (the decrease in the ice strength since the beginning of ice melt is 10–30%); a high specific discharge (30–70 l/(s km^2)) during a cold spring in the area of the ice-jam reach and intense snow melting (5–7 mm/day) in the upper part of the river basin against the background of heavy rains; and an intense ice drift (after the breakup) from the upstream river reach and from the tributaries during the breakup.

Weather conditions during breakup are important for the ice jam formation in particular years. For example, in the region of Velikii Ustyug Town, ice jams did not form in the years characterized by a drastic increase in air temperature in the period of breakup (1974) or by significant sums of liquid precipitation (1961). The temporal variability of the maximum ice-jam stages (Fig. 4) depends on a complex of factors, including different works for preparing the river for the breakup. In the region of Velikii Ustyug, the maximum water level in spring is due to ice jams in 57% of cases. This is the highest value for the Northern Dvina basin; at other gauges, the number of such cases varies within 12–50%.

In river basins of northern European Russia, larger or smaller ice jams are observed every year. In some years (1962–1964, 1946, 1953, 1970, and others), due to particular combinations of factors, ice jams were observed on more than one third of the ice-jam reaches. In some cases (1962–1964), ice jams were recorded on 60–80% of the ice-jam reaches. Yearly, ice jams were recorded at 25–30% of gauges on average.

Forecasts of the maximum ice-jam water levels $H_{\max}$ (or the levels during the ice drift in spring H_{ice}) [6] are commonly based on the predictors that characterize the conditions of freezing (the pre-freeze-up water level H_{pre}), freeze-up (maximum ice thickness h_{ice}), and breakup (the authors have chosen the increase in the water discharge in the time interval between the first advance and the preceding day ΔQ). The consideration

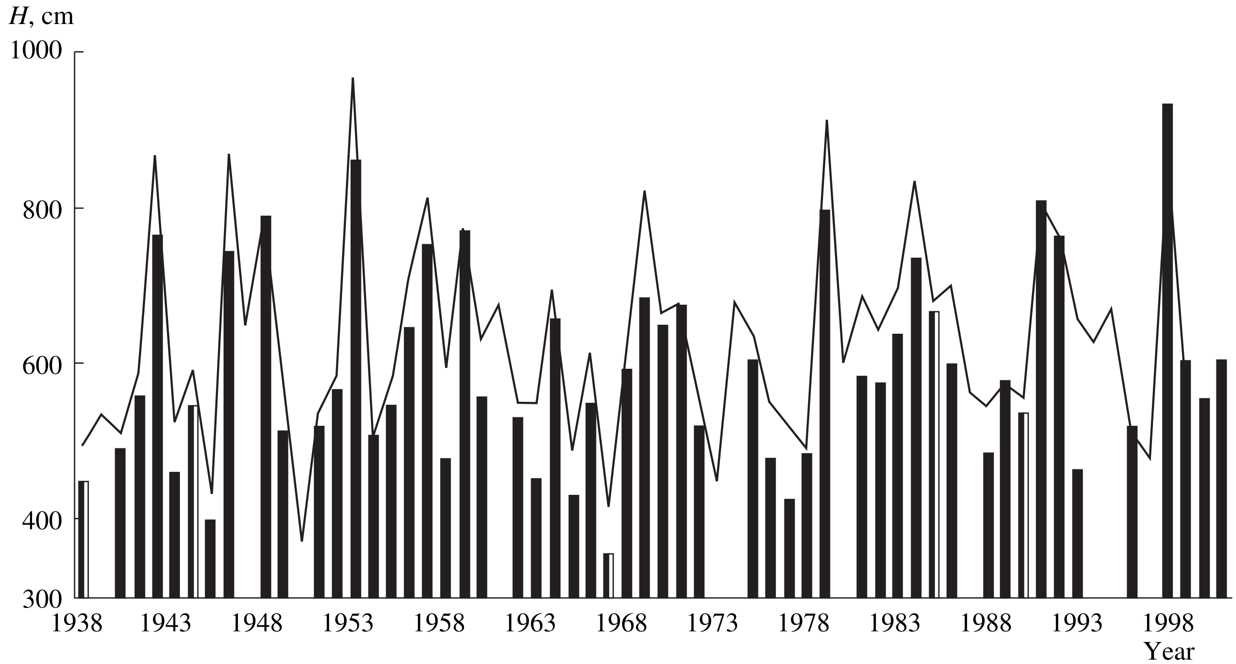

Fig. 4. Many-year variations in the maximum water level in spring (broken line) and the ice-jam water level (black columns) in the Sukhona near the town of Velikii Ustyug. *H* is the level above datum.

of all these factors for all ice-jam reaches in the Northern Dvina basin has shown that the maximum ice-jam level is best correlated with the water level in the period of freeze-up (the coefficients of pair correlation $r = 0.50–0.75$); the coefficient of correlation with the maximum ice thickness $r = 0.45–0.55$, and with the rate of water discharge increase $r = 0.45–0.60$. In the future, we suppose to increase the number of factors for the analysis of the ice jam formation in the Northern Dvina basin. Taking into account the fact that strong ice jams are rather frequent on the rivers of the Northern Dvina basin, we studied the spatial variability of the above-listed factors of ice jam formation. All initial series were converted into the series of anomalies normalized to the long-term mean. The variability of water levels in autumn and the ice thickness are governed by both the general climate changes and the local conditions. The variations in the water levels of the Sukhona, Yug, and Northern Dvina are more or less synchronous: the coefficients of correlation between the series of levels in the period of freeze-up $r = 0.6–0.7$. The Pinega basin is a special case where the river and its tributaries feature specific variations in water levels. The correlation between the anomalies of ice thickness on different rivers is much lower. The coefficients of pair correlation for this characteristic are 0.3–0.4 on the rivers of the Sukhona and Yug basins and 0.4–0.6 in the Pinega basin. The water level in the period of breakup is likely to be the main factor that governs the formation of the maximum ice-jam levels in a vast area; the ice thickness and the rate of increase in water discharges during breakup depend largely on local conditions.

The degree of hazard associated with strong ice jams in the Northern Dvina basin as a whole was assessed via the coefficient of extremity k equal to the percentage of ice-jam reaches with positive anomalies of water level, ice thickness, and so on. Climatologists applied similar coefficient to the assessment of the extremity and variability of climatic characteristics for vast areas [4]. The coefficient of extremity of climatic characteristics is the share of the area within which a certain anomaly is recorded in one or several characteristics. In this work, the coefficient k is calculated for the pre-freeze-up water level, the maximum ice thickness, the rate of the water discharge increase in the period of breakup, and the maximum ice drift stage in spring $k_{H_{\max}}$. Also, a common coefficient k_{tot} for three chosen predictors of the maximum ice-jam stage was calculated. The years with high coefficients k (1946, 1947, 1953, 1957, 1961, 1969, and 1979) are of special interest. The high value of $k_{H_{\max}}$ results from the combination of the very high k value for at least one predictor and mere high values for other predictors. Figure 5 demonstrates the relationship $k_{H_{\max}} = f(k_{\text{tot}})$ constructed for the ice-jam reaches in the Northern Dvina basin. As a rule, at high $k_{H_{\max}}$ values, ice jams form on many rivers when the water levels reach dangerous marks.

In addition to the general conclusion on the degree of hazard associated with strong ice jams in the Northern Dvina basin, local relationships can be elaborated for particular reaches and used to forecast the maximum ice-jam levels. However, this work requires much

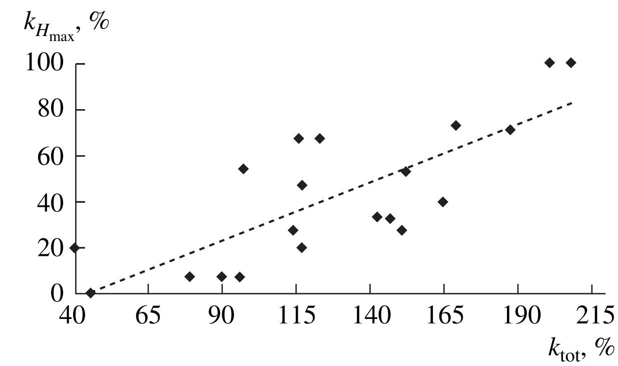

Fig. 5. The coefficient of extremety of the maximum ice-jam stage versus the total coefficient of extremity of its predictors $k_{H_{max}} = f(k_{tot})$ for the ice-jam reaches in the Northern Dvina basin. The dashed line corresponds to the regression equation.

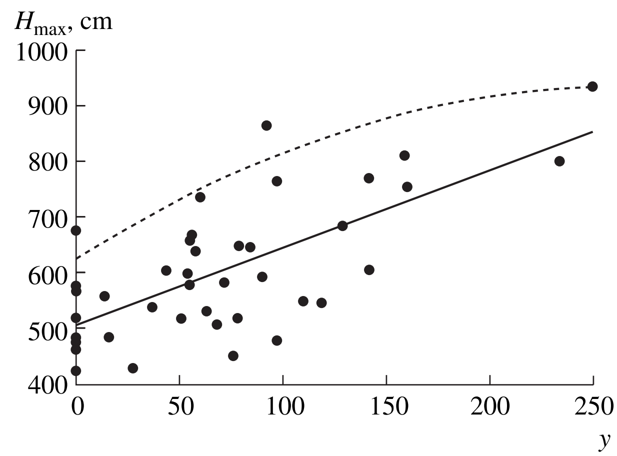

Fig. 6. Prognostic curve for the maximum ice-jam stages H_{max} in the Sukhona versus $y = \sqrt{\Delta Q(H_{pr} - h_{ice})}$ (the dashed line is the upper envelope of the relationship, the solid line corresponds to the regression equation).

time for collecting the needed information and choosing the practicable predictors. For example, when developing the prognostic relationship for the maximum ice-jam water levels H_{max} for the Sukhona near Velikii Ustyug Town, more than 20 possible predictors were analyzed [5]. As a result, the predictor $y = \sqrt{\Delta Q(H_{pr} - h_{ise})}$ was chosen, where H_{pr} is the water level in the Sukhona near Velikii Ustyug on the day of freeze-up, cm; h_{ice} is the maximum ice thickness over the period of freeze-up on the Sukhona near Velikii Ustyug, cm; and ΔQ is the rate of water flow increase in the Sukhona near Tot'ma Town over the period between the first ice advance and the preceding day. For the region of Velikii Ustyug Town, the forecast value obtained by the upper envelope of the relationship $H_{max} = f\sqrt{\Delta Q(H_{pr} - h_{ise})}$ exceeds the observed water levels by 100–200 cm (Fig. 6). For the Sukhona, the forecasts by the middle relationship for the flood periods of 2002–2005 gave good results.

The validity of the prognostic relationship is estimated by the expression: $s = \sqrt{V_k/\sigma}$ [11]

$$V_k = \frac{1}{n-k}\left(1 + \frac{k}{n-k-1}\right)\sum_{i=1}^{n}(H_a - H_c)^2,$$

where σ is the standard deviation of the initial series of the maximum ice-jam stages; n is the series length; k is the number of parameters; H_a is the actual values; and H_c is the calculated values of the maximum ice-jam stage. For the given prognostic equation $s = 0.76$; thus, the relationship can be considered valid.

Ice jams inflict considerable damage associated not only with the immediate flooding of the area but also with the reduction of navigation period (which is especially important for regions where railway communications are lacking), damage to ships in ship-yards, and losses of wood carried away by ice. The inflicted damage depends on the three main factors: the recurrence of the excess of the critical water level, the population density, and the genesis of emergency situations. These factors determine the possibility of forecast and measures for eliminating the emergencies. Of particularly hazard are the ice jams and the associated with them backwater levels in the regions of the towns of Kotlas and Shenkursk and Palauz Village, and other populated localities where ice jams cause the overflow of water onto the floodplain. Flooding of the towns of Vologda, Velikii Ustyug, Syktyvkar, and Arkhangelsk produces the most considerable damage.

Further studies of the ice regime in the given territory and the improvement of the forecast methods for the ice regime characteristics will serve to reduce the adverse effects of ice regime on the human economic activity.

CONCLUSIONS

No significant changes in the dates of freeze-up and breakup were recorded in the past century on the rivers of the Northern Dvina basin, except for the Northern Dvina itself and the Sukhona. A statistically significant moderation of ice regime is found in the Northern Dvina lower course: over 1880–2004, the dates of ice appearance became later (by 4–5 days) and the dates of breakup earlier (by 2 days). In the Sukhona upper course, the moderation of ice regime manifested itself in a much earlier (by 4 days) breakup. Calculations show that in the nearest decades, the dates of ice appearance will significantly change if the mean monthly air temperature increases by 1°C on average; the mean annual air temperature, by 2°C; and the rate of streamflow in autumn, by ~25%. Under the same conditions, the dates of breakup will change even less, shifting to earlier dates by mere 2 days. Thus, even considerable climatic changes in the nearest future will not lead to significant changes in the dates of ice phenomena in the Northern Dvina lower course.

The most important feature of the ice regime in the rivers of the Northern Dvina basin is the formation of ice jams. To assess the ice-jam hazard in the basin, the authors proposed the joint analysis of anomalies of the main predictors: the water level in the period of freeze-up, the maximum ice thickness, and the rate of water flow increase in the period of ice advance. The possibility to elaborate the local prognostic relationship is shown on the example of the Sukhona River near the town of Velikii Ustyug.

ACKNOWLEDGEMENTS

The study is supported by the Russian Foundation for Basic Research (project 06-05-64099).

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