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Flood dynamics on the Ob River at the city of Barnaul

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ABSTRACT:

Relevance. The growing economic damage from floods, which are observed regularly on the Ob River during high water and rainfalls, makes the study topical. Some districts of Barnaul are subject to flooding even at maximum water levels close to the average long-term ones. The statistical and historical-geographical analysis of floods for the observation period gives an idea of changes in their recurrence, genesis, and hazard class influenced by climate changes. **Methods.** The comprehensive historical, geographical and statistical analysis of floods on the Ob River, i.e. their genesis, flood probability, and impact for the period of instrumental observations (1894–2020) was used. To analyze trends related to climate change effects, we performed a comprehensive statistical analysis of maximum water levels (as the main characteristics of floods). It includes the study of hydrological series homogeneity, the calculation of ordinates and construction of flood probability curves in conditions of instability, the analysis of the frequency of floods of different exceedance probability and genesis before climate changes (1976) and at present. **Results.** During the observation period of 1894–2020, a general decline in maximum water levels is observed. The trend is statistically significant at the 1 per cent level due to intra-annual runoff redistribution because of climatic changes: an increase in winter low water flow and a decrease in the snowmelt component of high water flow. It is found that with the beginning of climate changes, the snowmelt flood frequency halved; flood probability of less than 10 per cent was recorded only once during rainfalls in 2014. In the high-water period, snowmelt provides more than half of cases of Barnaul floods. However, the proportion of such floods has reduced since 1976. At the same time, the share of rapidly developing rainfall floods has doubled.

Keywords: the Ob River, Barnaul, maximum water level, statistical analysis, snowmelt flood, flood, high water, ice blockage, flooding, flood probability, climatic changes.

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INTRODUCTION

According to Roshydromet, since the early 1990s, there has been an increase in natural disasters accompanied by economic damage due to high water and rainfall floods, with the share of the latter increasing[1]. Rapidly developing rainfall floods caused the largest inundations of the 21st century in the basins of the Adagum (2012) [1], the Amur (2013) [2], the Angara (2019) [3]. The rainfall flood in 2014 led to the highest water discharge for the entire observation period on a number of rivers in the Upper Ob basin [4, 5]. In 2024, there was a flood in the Ural River basin, which affected the Orenburg, Kurgan and a number of other regions of Russia and the Republic of Kazakhstan. This flood had a different genesis and was formed mainly by melt water due to a combination of the following factors: low infiltration capacity of soils (because of their overwatering and deep freezing), significant snow accumulation and quick spring [6]. The anthropogenic factor – development of floodplains, construction of roads, bridge crossings of low capacity – raises the scale of hazardous events due to high water and rainfall floods, and aggravates their consequences [1, 7].

The climate changing, flood damage is expected to enlarge further because of increasing annual river runoff, rising extreme precipitation and growing snow accumulation during cold winters [8].

The purpose of this study is to analyze the dynamics and genesis of maximum water levels of low exceedance probability under conditions of climate changes (using the Ob River within the city limits of Barnaul as an example).

Floods are regularly observed on the Ob River. Historic documents contain information about the flood in Barnaul in 1793. In [9], based on historic sources, the chronology of the flood events is reconstructed. Heavy snowfalls, late onset of spring with a surge of warm spell and heavy rain, late Ice break-up began on May 1 (May 12 in the new style), are considered to be the causes. Even taking into account that the described events belong to the epoch of the so-called Little Ice Age [10], the ice began to drift on the Ob very late, on May 4-5 (May 15–16 in the new style), while usually in those times it was on April 1–20 (April 12 – May 1 in the new style) [9].

In the 20th century, the most raging and destructive floods documented were observed in 1928, 1937, and 1969. The winter of 1927–1928 was unusually snowy. On April 10, 1928, the newspaper "Krasny Altai" published "A Warning about a possible flood"[2]. The rapid growth of the water level was connected with a warm spell surge, the situation worsened because of the ice blockage near the tannery and the settlement of Ilyich. The maximum water level on the Ob amounting to 711 cm above the zero of the water-measuring station was observed on April 24[3].

[1] The Third Assessment Report on Climate Change and its Impacts on the Territory of the Russian Federation. St. Petersburg, 2022. 676 p.
[2] Krasny Altai. Barnaul. 1928. No. 85.
[3] Krasny Altai. Barnaul. 1928. No. 97.

In the spring of 1929 the flood was accompanied by two big ice blockages and floods[4], the maximum level being a little earlier, on April 16, amounting to 692 cm. In the following years, ice dam floods of such a scale on the Ob River in Barnaul were not observed.

The winter of 1936–1937 was also snowy. In this regard, the Presidium of Barnaul City Council on March 21, 1937 published a resolution "On flood control"[5]. The flood of 1937 in many respects repeated the scenario of 1793. The ice drift on the Ob started late – in early May. On May 3, the water level rose to 483 cm, heavy precipitation observed. By May 10 the water level in the river reached 645 cm, and on May 16 – 763 cm above the zero of the water-measuring station.

In 1969, there was another raging flood caused by significant snow accumulation. Besides, the soil in the catchment area froze to a great depth due to severe and prolonged frosts. The water level reached catastrophic levels twice: the first time on May 6 as a result of a quick spring with heavy rains – 684 cm, and the second time a month later, on June 5–6, as a result of snowmelt in the mountainous part of the basin – 737 cm. (Fig. 1*a*).

The next, and currently the last, catastrophic flood was in Barnaul in 2014. It was caused by abnormally heavy extreme rainfall in the Altai foothills in late May – early June (Fig. 1*b*), and the year was relatively snow-free [4], the level reaching the 702 cm mark.

SUBJECT AND METHODS OF RESEARCH

The subject of research is a section of the Ob River in its upper reaches, within Barnaul. Upstream, there are no large reservoirs on the Ob and its largest tributaries, and the backwater zone of the Novosibirsk reservoir does not extend to the area under consideration, so the change in runoff characteristics is mainly due to the influence of climatic factors [11]. The main phase of the water regime is the flood, during which from 40 to 80 per cent of the annual runoff passes. The water regime of the Ob formed mainly in the Altai mountainous region with uneven snow melt in different altitudinal zones, the flood is long, from April to July, having two or three waves. The maximum of the first wave is observed in mid-April – early May, the second wave – in late May – early June. Maximum annual water levels and dangerous hydrological phenomena associated with them are observed most often during the second wave of the flood, they are formed due to snowmelt in the mountains. The Ob, like other Siberian rivers, is characterized by the formation of ice blockages, but they do not usually occur near Barnaul. The average multiyear maximum water level is 560 cm above the zero of the water gauging station. The maximum level was observed on May 16, 1937 – 763 cm. The lowest maximum level was observed in 2012, July 20 – 285 cm. Some neighborhoods of Barnaul are

[4] Krasny Altai. Barnaul. 1929. No. 87.
[5] Krasny Altai. Barnaul. 1937. No. 61.

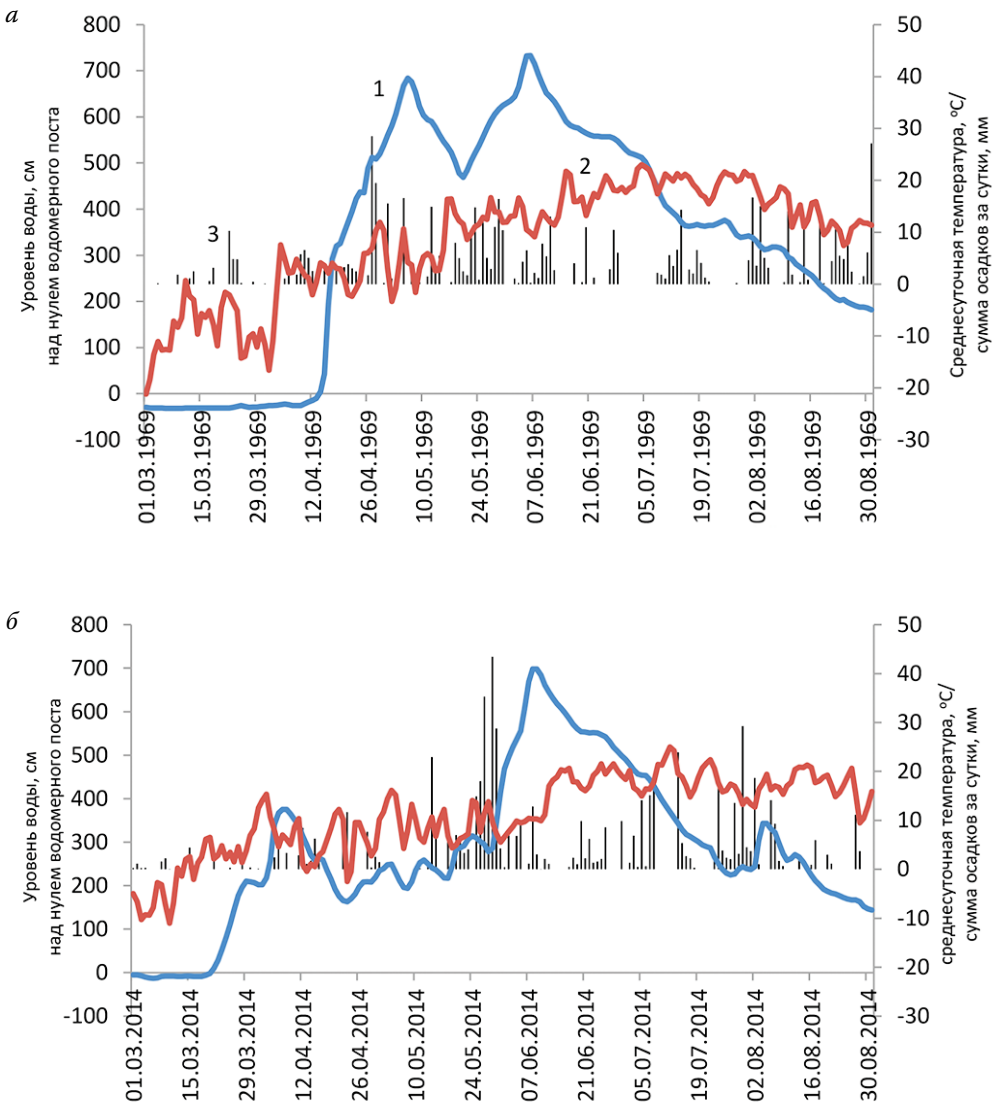


Fig. 1. A complex graph of hydrometeorological components during high water of 1969 (*a*) and 2014 (*b*): 1 – the Ob water level at Barnaul; 2 – the average daily temperature; 3 – the precipitation amount at the gauge Kyzyl-Ozek and Yaylu.

regularly flooded during the flood period. According to the data of the Barnaul City Administration[6], the flood mark of the district of Zaton is 560 cm (corresponding to its flood level). The settlement of Ilyich is 650 cm above the zero of the water gauge. Water outflow to the floodplain begins when the water level reaches 500 cm above the zero of the water gauge.

The main indicator characterizing floods is the maximum runoff, expressed in terms of maximum discharge or water levels [12]. In the authors' opinion, it is preferable to use level series rather than flow series as the most important criteria for floods are the magnitude and probability of exceeding the "dangerous" elevation at which flooding of residential areas begins. Increasing of levels is not always directly related to increasing discharge (e.g. in the case of ice dam). It should also be taken into account that close to the maximum water discharge on the Ob River is when the floodplain is flooded. In this case, there may be significant errors in accounting for the floodplain component of the discharge when constructing and extrapolating the water discharge curve. As a consequence, significant errors are likely in determining the discharge [13], the Barnaul section of the Ob included [14]. Statistical analysis and calculation of maximum water levels are a reliable basis for subsequent work on defining flood zone boundaries and designing in river basins as the levels measured at water gauging stations integrally reflect all factors determining their formation [15].

In this regard, this study uses as the main source of baseline information the data on annual maximum water levels at the hydrological post (HP) of the Ob River – Barnaul for the period from the beginning of instrumental observations in 1894 to 2020, published in the reference publications of the State Water Cadastre[7], "Hydrological Yearbooks"[8,9] and "Automated System of State Monitoring of Water Bodies"[10]. In addition, data on dangerous hydrological phenomena from the archive of the Federal State Budgetary Institution "VNIIGMI-MCD" "Unfavorable weather conditions that caused economic losses"[11] were used. The archive contains information on floods and high water that caused increasing levels to marks at a recurrence rate of less than 10 per cent for the period from 1991 to 2023.

In order to assess the multi-year dynamics of maximum levels, there was constructed a linear trend, the significance of which was assessed in accordance

[6] Electronic resource: https://barnaul.org (date of reference: 1.02.2025).
[7] State water cadastre. Characteristic levels of rivers, canals, lakes, reservoirs (weather data). Issue. 10. Basins of the Ob (without the Irtysh basin), Nadym, Pur, Taz rivers. L.: Gidrometeeoizdat, 1988. 256 p.
[8] Hydrological Yearbook. Vol. 6. The Kara Sea basin (western part). Issue. 0-3.L., 1949–1966.
[9] Hydrological Yearbook. Vol. 6. The Kara Sea basin (western part). Issue 0–3: the Ob River and its basin up to the mouth of the Irtysh River. Novosibirsk, 1968–1990.
[10] Electronic resource: https://gmvo.skniivh.ru (date of reference: 1.02.2025).
[11] Electronic resource: http://meteo.ru (date of reference: 1.04.2025).

with the HSI[12] recommendations by the random mean square error of the correlation coefficient σ_r:

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

At $\frac{r}{\sigma_r} \geq \beta$, the trend is significant. At the level of significance $\alpha = 5$ per cent $\beta \approx 2$, at $\alpha = 1$ per cent $\beta \approx 3$.

The probability of exceeding maximum water levels (flood probability) was a flood hazard criterion. This indicator is the basis for the hazard classification of floods developed by B.M. Dobroumov and S.M. Tumanovskaya in accordance with the classification of the Ministry of Emergency Situations [12]. To assess socio-economic damage (scale, area of flooding of settlements, number of affected population, etc.) in dynamics is impossible because the area and nature of development, channel and floodplain morphology, and approaches to damage assessment have changed too much.

Climatic changes in recent decades have led to violating stationarity of river flow formation conditions. Therefore, the first and obligatory stage in statistical analysis of hydrological characteristics is checking series for homogeneity. The series were checked using Fisher's and Student's criteria, as well as Pettitt's test, Standard normal homogeneity test (SNHT), and Buishand range test [16]. A similar approach was implemented earlier when assessing climate-induced changes in the runoff of the rivers of the Upper Ob basin [17]. The year of homogeneity violation was determined using Pettitt's test, SNHT, Buishand range test [16], as well as with difference and sum integral curves.

There are used various approaches to assess probability of exceeding hydrological characteristics under conditions of nonstationarity caused by the influence of climatic changes (anthropogenic factors, such as the construction of large hydraulic structures, are not considered here).

The State Hydrological Institute recommends to use truncated or composite probability curves[13] in the case of heterogeneous observation series, with historic (outstanding) maximum of rare recurrence considered by all means[18].

The problem of assessing and forecasting both extreme values of hydrological characteristics and multiyear runoff fluctuations in nonstationary

[12] Methodical Recommendations on Assessment of Hydrological Characteristics Homogeneity and Determination of Their Estimated Values Based on Heterogeneous Data. St. Petersburg: Nestor – History, 2010. 162p.

[13] STO GGI 52.08.41-2017 Main hydrological characteristics with non-stationarity of time series caused by the influence of climatic factors. Recommendations for calculation. St. Petersburg:Federal State Budgetary Institution of the State Hydrometeorological Institute, 2017, 46 p.

conditions is successfully solved using Bayesian approaches [19–21]. The main advantage of the latter is that it is possible to determine the estimated hydrological characteristics of phenomena of rare recurrence under conditions of uncertainty of climatic changes, taking into account various climate change scenarios [19, 21].

In accordance with modern regulatory documents[14], in case of heterogeneity of hydrological series due to natural factors or climate change, empirical and analytical distribution curves are constructed separately for each homogeneous series using composite curves or the sum of distributions based on Bayesian approaches.

In this paper, a composite curve according to SP 529.1325800.2023 was constructed to calculate the maximum levels of a given probability. Smoothing and extrapolating empirical curves for homogeneous periods were performed with the three-parameter Kritsky – Menkel distribution. Determination of ordinates of analytical curves was performed using the approximate maximum likelihood method. Parameters of the composite probability curve (for two genetically homogeneous elements) were calculated using the formula:

$$P_{\%} = \frac{n_1 P_1 + n_2 P_2}{n_1 + n_2}, \quad (2)$$

where P_1, P_2 are the values corresponding to the given probability, and n_1, n_2 are the lengths of each of homogeneous samples.

In accordance with the classification [12] there are distinguished catastrophic floods (less than 5per cent probability), dangerous floods (5–10 per cent), high floods or rainfall floods (11–25 per cent) and medium floods or rainfall floods (26–40 per cent). Probability of annual maximum water levels calculated and the years of floods highlighted, each event was assigned a hazard class.

Another important indicator of floods is their genesis. In Siberia, snow and rain floods are the most frequent causes of floods; ice dams are somewhat less common. Floods are often caused by a combination of several factors [3]. To assess the genesis of floods, we constructed complex graphs of hydrometeorological elements, including the course of water levels on the Ob River at the city of Barnaul, the sum of precipitation and air temperature at representative meteorological stations Kyzyl-Ozek and Yailu. Floods of the early 20th century were assessed with the method of historical and geographical analysis based on literary and archival data as "Hydrological Yearbooks" have been published only since 1936.

[14] SP 529.1325800.2023 "Determination of basic design hydrological characteristics"

RESULTS AND DISCUSSION

Multiyear dynamics of maximum water levels

During the period of instrumental observations on the Ob River at the city of Barnaul, there was a decrease in maximum water levels (Fig. 2) and discharge [11], despite the general increase in the river water content [22, 17]. The ratio of the correlation coefficient of the linear trend to its RMS $\frac{r}{\sigma_r}$ = 3,33, i.e., the trend is significant at the significance level α = 1 per cent.

The series is homogeneous by dispersion (*F*-criterion value of 1.15 with a critical value of 1.87), but heterogeneous by mean value (*t*-criterion of 3.67 with a critical value of 2), which confirms the significance of the linear trend.

In order to construct a composite probability curve, the series was divided into two conditionally homogeneous periods (Fig. 3). The moment of homogeneity violation cannot be unambiguously distinguished on the integral curves; a downward deviation of the total integral curve can be traced starting from the mid-1970s. According to Pettitt's test and Buishand range test, the stepped "break" is determined in 1961.

Taking this into account, there were constructed analytical curves of maximum water level distribution for homogeneous periods of 1894–1960 and 1961–2020, on the basis of which a composite curve was constructed. Table 1 presents the results of calculation of maximum water levels of a given probability for homogeneous periods and the composite curve.

Table 1. Maximum water levels at specified exceedance probability for homogeneous periods and a composite distribution curve

Period	Provided values of maximum levels with probability of exceedance, cm above the zero of the gauging station										
	P, %										
	1	5	10	15	20	25	30	35	40	45	50
1894–1960	719	682	657	645	633	621	612	604	596	589	581
1961–2020	727	676	641	624	607	591	578	567	556	546	536
1894–2020	723	679	653	637	622	608	596	587	578	570	561

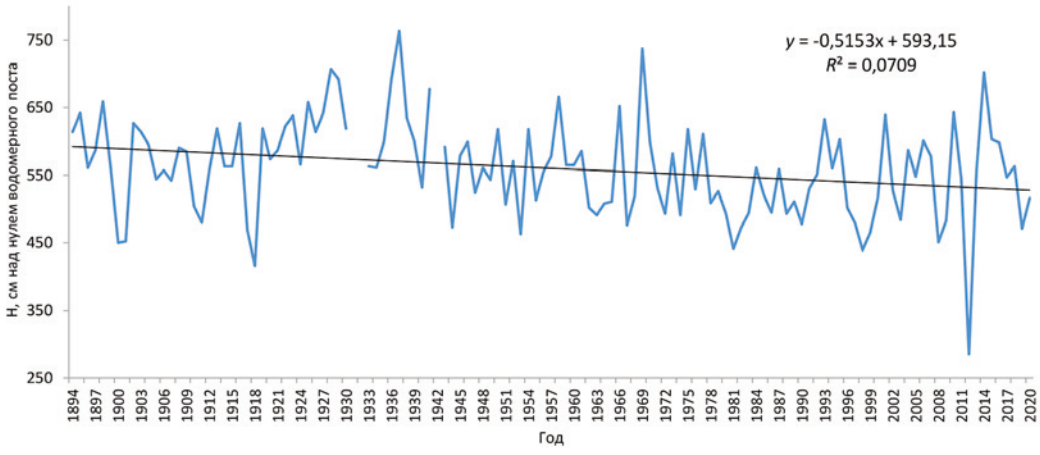


Fig. 2. Maximum water levels of the Ob River at the city of Barnaul in 1894–2020.

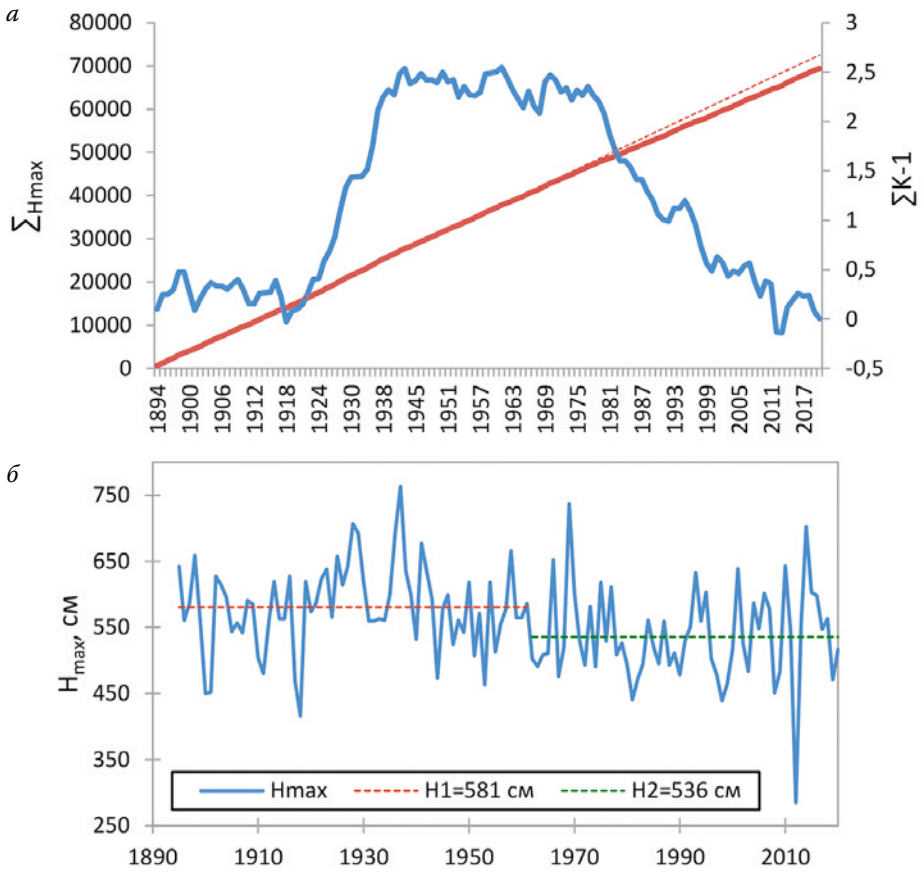


Fig.3. Differential and total integral curves of maximum water levels (*a*); results of the Pettitt's test-based homogeneity analysis (*b*).

In accordance with Table 1 and [12], all floods were classified as follows: catastrophic floods (less than 5 per cent probability) – with water levels above 679 cm; dangerous floods (5–10 per cent) – from 679 to 653 cm; high floods (11–25 per cent) – from 654 to 608 cm; medium floods (26–40per cent) – from 609 to 578 cm (Fig. 4, Table 2).

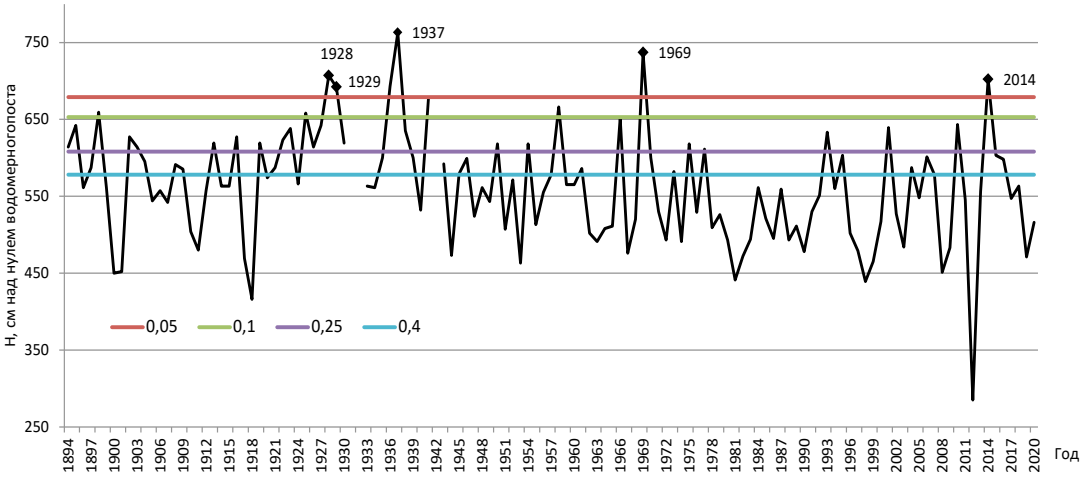


Fig. 4. Maximum water levels (1894-2020) and specified exceedance probability.

Table 2. Barnaul floods during the period of 1894–2020

Flood hazard class according to [23]	*P*, %	Years
Catastrophic	Less than 5	1928, 1929 , 1936, 1937, 1969*, 2014
Dangerous	5–10	1898, 1925, 1941*, 1958*
High	11–25	1894,1895, 1902, 1903, 1913, 1916,1919, 1922, 2923, 1926, 1927, 1930, 1938, 1950, 1954*, 1958* 1966, 1975, 1977, 1993, 2001, 2010
Medium	26–40	1897, 1908, 1909, 1921,1935, 1939, 1941* 1943, 1945, 1946, 1954* 1961, 1970, 1973, 1995, 2004, 2006*, 2015, 2016

* – years with a repeated rise in the level of a given probability of exceedance.

Genesis of floods

On the Ob, as on most snow-fed rivers, maximum water levels are usually observed during the snowmelt flood season. The most destructive floods are usually formed by a combination of several factors: a cold and snowy winter, a quick spring, heavy precipitation during the flood season, and Ice dams; one or two factors being predominant.

Thus, all catastrophic floods of the 20th century were preceded by snowy winters, liquid precipitation during the snowmelt period only contributed to an additional rise in the level. In 2014, the flood was caused by heavy rainfall in the mountainous part of the basin in late May (Fig. 1*b*). Floods of a less than 5 per cent probability caused by ice blockages during the snowmelt period were observed in 1928 and 1929. After the 1940s, there were no ice dams in Barnaul, which is probably due to changes in channel morphology as a result of river bed evolution, as well as climate warming and reduction of ice thickness.

With the constructed complex graphs of hydrometeorological elements starting with the year of 1936, there were identified the main factors contributing to the formation of floods in the given year. By genesis they were categorized as snowmelt floods, rainfall floods and floods of mixed origin. Mixed floods were if a clearly defined peak on the hydrograph was synchronized with an increase in average daily temperatures and a significant amount of liquid precipitation. In some multi-snow years, exceeding levels corresponding to 40 per cent probability and less were observed more than once (twice in 1954, 1958, 1969, and 2006, and three times in 1941); each case being analyzed separately.

Presumably, changes in the genesis and frequency of floods are related to climatic factors, so a comparative analysis of two periods was performed – before the beginning of intense temperature rise (from 1936 to 1976) according to [23] and after it (Table 3). The periods are almost identical in duration – 40 and 44 years, respectively, so the comparison, in our opinion, is quite relevant. The period before 1936 was not included in the analysis due to the lack of hydrometeorological information and the impossibility to determine the genesis of floods with sufficient reliability.

Since 1977, the frequency of floods has almost halved compared to the previous period. From 1978 to 1992 there were no floods at all. Genetic analysis showed that both before the global warming and in the modern period, more than half of floods in Barnaul were caused by snowmelt floods (Table 3), although after 1976 their share slightly decreased. At the same time, the proportion of rainfall floods has almost doubled.

The reduced number of floods categorized as catastrophic and dangerous is particularly striking. At the present time there was such a flood only once in 2014, with the maximum level of 702 cm above the zero of the water gauge corresponding to 3 per cent probability. However, it should be noted that there has been a slight

Table 3. Number and genesis of Barnaul floods in 1936–1976 and 1977–2020

Period	Number	Frequency	Genesis (% of total for the period)		
			Snowmelt floods	Rainfall floods	Mixed floods
1936–1976	21	5,2 times/ 10 years	13 (61,9 %)	3 (14,3 %)	5 (23,8 %)
1977–2020	11	2,5 times / 10 years	6 (54,5 %)	3 (27,3 %)	2 (18,2 %)

increase in the number of floods since the early 1990s compared to the previous 20-year period. The flood mark of 560 cm has been exceeded 11 times since 1991.

Thus, despite the overall increasing water content, there is a decrease in the maximum water levels and the frequency of low exceedance probability floods in the upper reaches of the Ob River. The reason, in our opinion, is the following. Earlier we found that due to climatic changes in the rivers of the Upper Ob basin the share of winter low-water in the annual runoff is increasing and the share of snowmelt water runoff is decreasing. Violation of winter runoff homogeneity is observed everywhere; in some cases, the flood runoff is also heterogeneous [17]. Such trends are characteristic of rivers with a significant share of snow feeding [23, 24]. They are associated with increasing thaws, a decreasing depth of soil freezing and a rise of its water absorption capacity in winter. In addition, in the Ob River, due to the shift of snowmelt to earlier dates, the runoff grew in the first wave of the flood, in April, and fell in the more high-water second wave, in May-July. [11]. At the same time, there is a rise in the proportion of fast-developing floods due to extreme rainfalls, which is typical of the Russian territory as a whole[15].

RESUME

The climatic changes observed in recent decades have significantly affected the level regime of the Ob River and, consequently, the frequency of floods. Analysis of a series of more than 120 years showed a decrease in maximum water levels. The linear trend is considered to be significant at the 1 per cent level. Reduced maximum levels and, consequently, the frequency of floods are associated with redistribution of runoff within the year – a growing winter low-water period, a decreasing melt component of the flood runoff, especially in its more high-water second wave.

[15] The Third Assessment Report on Climate Change and its Impacts on the Territory of the Russian Federation. St. Petersburg, 2022. 676 p.

Taking into account the heterogeneity of the series, a composite distribution curve of the probability of exceeding maximum water levels was constructed, and the levels of a given probability were determined. Based on the results of statistical and genetic analysis, a hazard class was assigned to floods of 40 per cent probability and below, their genesis determined.

A comparative analysis of the frequency of occurrence of floods of different genesis and hazard class before beginning of climate changes in 1976 and in the modern period was carried out. It was found that after 1976, the frequency of floods almost halved, and floods with a probability of less than 10per cent were observed only once – in 2014. The proportion of floods caused by snowmelt decreased from 62 per cent (before 1976) to 55 per cent in the modern period, while the proportion of fast-moving rainfall floods doubled. In the modern period, no snowmelt floods of less than 10 per cent probability have been observed. The increasing frequency of rainfall floods, including those during the snowmelt flood season, leads to a decreasing predictability of the maximum snowmelt floods.

Thus, climatic changes do not always contribute to increasing frequency of hydrological hazards, even under conditions of general rising of river water runoff. The seemingly favorable trend of decreasing flood frequency leads to intensification of economic development of the riverside, which, in turn, increases the risk of catastrophic flooding.

CONFLICT OF INTERESTS

The authors declare no relevant conflict of interests.

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