

Article

Changes in the Frequency of High- and Low-Flow Years in the Permafrost-Dominated Lena River Basin During Long-Lasting Phases of Contrasting Water Flow

Alexander G. Georgiadi ¹, Irina P. Milyukova ¹, Oleg O. Borodin ¹ , Elena A. Barabanova ¹, Pavel Y. Groisman ^{2,3,*}  and Yuriy Y. Alent'ev ¹

¹ Institute of Geography, Russian Academy of Sciences, 119017 Moscow, Russia; georgiadi@igras.ru (A.G.G.); milukova@igras.ru (I.P.M.); oleg-borodin@yandex.ru (O.O.B.); barabanova@igras.ru (E.A.B.); alentev49@mail.ru (Y.Y.A.)

² Cooperative Institute for Satellite Earth System Studies, North Carolina State University, Asheville, NC 28801, USA

³ Hydrology Science and Services Corporation, Asheville, NC 28804, USA

* Correspondence: groismanp@bellsouth.net

Abstract

Long-term phases (lasting 10–15 years or more) of decreased and increased annual and seasonal runoff and related differences in the frequencies of low-water and high-water river flow years were identified for the Lena across Kyusyur and Tabaga and its tributary, the Aldan in Verkhoyanski Perevoz, for observation periods beginning in the 1930–1940s. Phase boundaries were identified by cumulative deviation curves and the statistical homogeneity of runoff time series. The frequencies of abnormal years were estimated based on the empirical exceedance probability curves, derived from multi-year time series of annual and seasonal flows. Two main long-lasting, quasi-synchronous contrasting phases were revealed on each of the rivers under consideration during an 80-year series of observations for both annual and seasonal runoff. At first, there was a phase of decreased runoff, which was followed by a phase of increased runoff during the period of modern global warming. These contrasting phases exhibit quasi-synchronicity not only within the same river but also across different rivers. However, the duration and magnitude of the flow difference between phases vary both on each river and between them. The phases of increased runoff are characterized by a noticeably higher frequency of high-water years (when runoff is at least 25% of the exceedance probability) and a lower frequency of low-water years (when runoff is at least 75% of the exceedance probability). This inverse relationship has been revealed for the phases of decreased runoff.

Keywords: permafrost-covered large river basins; annual and seasonal river runoff; long-lasting phases of decreased/increased runoff; frequency of low-water and high-water flow years; global warming



Academic Editors: Bommanna Krishnappan and Jueyi Sui

Received: 15 April 2026

Revised: 26 June 2026

Accepted: 17 July 2026

Published: 24 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Contemporary global warming has brought about clear changes in various components of the natural environment, including river runoff [1,2]. Many publications are devoted to the study of long-lasting contrasting periods regarding multi-year variations in runoff in different regions of the world [3–12]. These contrasting periods (termed “phases” in the USSR and Russia [13]) are characterized by specific, relatively steady river water

regimes [6]. They constitute a significant part of the overall long-term variability of river runoff caused by climate change. In most cases, the differences in the average runoff of such phases are statistically significant [8]. There is experience in using parametric and nonparametric criteria to assess the statistical uniformity of the runoff time series based on its average values [14–17]. The phases commonly last 10–15 years or more, even extending over several decades. It has been established that the long-term dynamics of contrasting phases in relation to the world’s largest rivers are asynchronous [12]. In the territory of Russia, where the water regime is dominated by snowmelt flood flow, the years of the annual runoff contrasting phase transition, associated with the onset of modern global warming, change in the meridional types of circulation [18]. The main characteristics (phase duration, runoff differences between them) have been assessed for the rivers of Northern Eurasia [5–11], Europe [4], Asia [10,11] and Africa [3]. For the East European Plain and Siberia, several characteristic types of long-term dynamics of seasonal-scale contrasting phases of annual runoff and runoff have been identified [5–7].

In the East European Plain, against the background of long phases of decreased/increased flow, years are identified in which extremely low flow is observed, caused by the most severe droughts affecting large river basins. These occur not only in the summer–autumn period, but also in other seasons and over the year as a whole. Abnormally low and high runoff between seasons and annual runoff are fairly typical for this region. Their frequency during long phases of contrasting annual and seasonal runoff differs significantly. This issue has been studied to a much lesser extent in relation to river flow between hydrological seasons [6]. Also, the question of how the frequency of low- and high-water years is related to long phases of increased/decreased annual and seasonal runoff remains understudied.

The primary objectives of our study were (1) to identify the boundaries of long-term phases of increased/decreased annual and seasonal runoff and to assess their characteristics (boundaries, duration, and average runoff) and (2) to estimate the number of years with low and high runoff for the major rivers of the Lena River Basin—one of the largest river basins in the world. This Basin is almost entirely covered by permafrost. The main study areas included the entire Lena River Basin up to the Kyusyur gage station; the basin of the Lena River’s largest right-bank tributary, the Aldan River; and the Lena River Basin up to the confluence of the Aldan River. The working hypotheses are that in the phases of increased runoff, the frequency of high-water years notably increases, while the frequency of low-water years decreases, and vice versa. Furthermore, the difference in the frequency of such years depends on the hydrological season of the year.

2. Materials

2.1. Study Area

The Lena River catchment in the village of Kyusyur is one of the largest in Russia (Figure 1) and is over 90% permafrost (Table 1). Most of the territory is occupied by taiga forests and tundra. This vast region is characterized by a sharply continental climate.

Table 1. Main characteristics of the river basins studied.

River Gauge	Basin Area, 10 ³ km ²	Proportion of the Basin with Elevation ≥1000 m, % [19]	Share of Main Natural Zones *, % of the Basin Area [20]	Permafrost Share (All Types), % of the Entire Basin Area [21]	Main Reservoirs’ Total Capacity, km ³ [22]
Lena–Kyusyur	2430	17	Tu: 22 T: 71 I: 7	94	35.9

Table 1. *Cont.*

River Gauge	Basin Area, 10 ³ km ²	Proportion of the Basin with Elevation ≥1000 m, % [19]	Share of Main Natural Zones *, % of the Basin Area [20]	Permafrost Share (All Types), % of the Entire Basin Area [21]	Main Reservoirs' Total Capacity, km ³ [22]
Lena–Tabaga	897	25	T: 93 I: 7	99	0
Aldan–Verkhoyanski Perevoz	696	22	Tu: 18 T: 78 I: 4	93	0

Note(s): * TU—tundra, T—taiga, and I—Intrazonal (swamps and others).

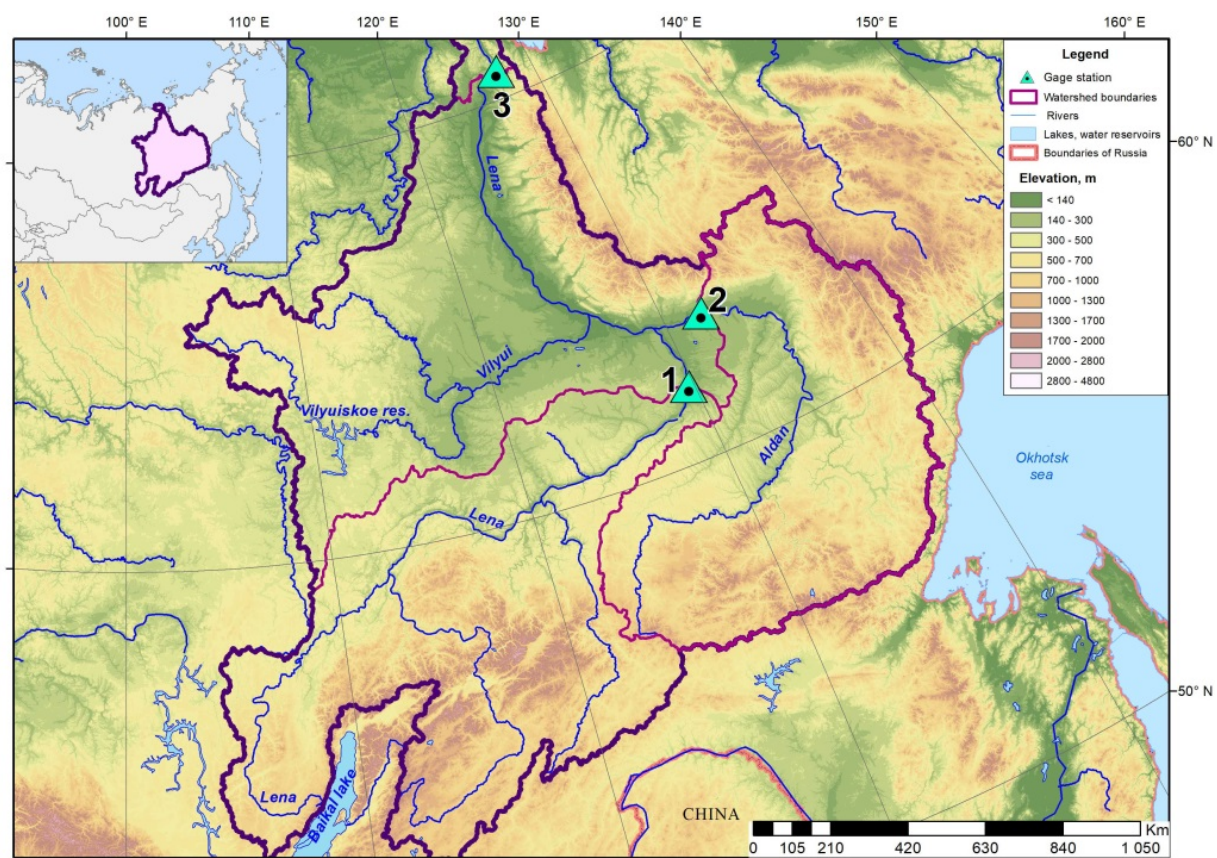


Figure 1. The Lena catchment. The flows studied here are measured at gauges on (1) the Lena River across Tabaga, (2) the Aldan River in Verkhoyanski Perevoz, and (3) the Lena River across Kyusyur. Map projection: Lambert Azimuthal Equal Area (central meridian 20° E, latitude of origin 45° N).

Runoff during the spring–summer flood period accounts for approximately 60% of the annual flow in the lower Lena near Kyusyur (where the flood lasts longer than in the upper and middle parts of the Basin) and over 40% in the Lena near Tabaga and Aldan (Table 2). During the decline of the snowmelt flood, rain floods make a certain contribution to its volume. Between 30 and 50% of the annual flow occurs during the summer–autumn period, and during this period, it is formed by rainfall and groundwater recharge. Winter runoff (from November to April), when the river is covered with ice, accounts for less than 10% of the annual flow.

Table 2. Characteristics of the flow of the studied rivers, averaged for the entire observation period.

River–Gauge	Period of Observation	Mean Annual River Runoff, m ³ /s	Mean Daily Water Discharge, m ³ /s		
			Spring–Summer Snowmelt Runoff	Summer–Autumn Runoff	Winter Runoff
Lena–Kyusyur *	1936–2019	17,176	40,489	22,961	2621
Lena–Tabaga	1936–2022	7300	18,077	10,743	1406
Aldan–Verkhoyanski Perevoz	1942–2022	5453	14,921	7882	677

Note(s): * naturalized water discharges (for the restoration method see Section 2.2).

The average long-term volume of water flow for the entire observation period reaches 542 km³ in the Lena across Kyusyur, 230 km³ in the Lena across Tabaga, and 172 km³ in the Aldan.

The main anthropogenic influences on the Lena flow, especially in winter, are due to the long-term regulation reservoir on the left tributary, the Vilui, which flows into the Lena downstream of Yakutsk city. The total volume of the reservoir, which was filled in 1966, is 44.4 km³, and its active storage capacity is 22.4 km³. Other types of anthropogenic impact have an insignificant effect on the river flow and water regime of the Lena and Aldan.

2.2. Data

The study was based on long-term hydrometric observations conducted at the network of Roshydromet stations. The Lena River’s flow records across Kyusyur, for the period following the start of filling the Vilyui Reservoir, were naturalized by transforming the annual hydrograph of daily water discharges [8] via a linear model describing the relationship between water discharges at the inlet and outlet of the river reach under consideration, using Kalinin–Milyukov influence functions [23].

The boundaries of hydrological seasons, which were assumed to be constant for the entire observation period, were determined by analyzing long-term records of monthly water discharges, as well as of river freezing and ice cover destruction [6].

3. Methods

3.1. Detection of Transition Years for Phases of Contrast Annual and Seasonal Water Flow

The transition years between long phases of contrasting annual and seasonal water flow were identified using cumulative deviation curves (based on their maximum and minimum coordinate values) in combination with an assessment of the statistical homogeneity in the runoff time series between adjacent phases using their mean values. The nonparametric homogeneity test was applied for this purpose [5–7].

3.1.1. Cumulative Deviation Curves

Cumulative deviation curves (CDCs) represent the cumulative sum of deviations of a given characteristic from its mean value, calculated over the entire observation period [7,24]. The values of normalized cumulative deviation curves are calculated as follows:

$$CDC_{\tau} = \frac{1}{C_v} \sum_{i=1}^{\tau} (K_i - 1)$$

$$K_i = E_i / E_m$$

$$C_v = \frac{\sigma}{E_m}$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (E_i - E_m)^2} \quad (1)$$

where CDC_τ is the value of the cumulative deviation curve for year τ ; E_i is the value of the i th member of the time series ($i = 1, \dots, n$); n is the number of members in the time series; E_m is the average long-term value; K_i is the modular coefficient of the i th member of the time series; C_v is the coefficient of variation of the time series; and σ is the standard deviation.

3.1.2. Criteria for Statistical Homogeneity of Long-Term Time Series of River Water Flow Based on Their Mean Values

The Mann–Whitney–Pettitt (MWP) test [25] from the AnClim 5.025 package [26] was used to assess the statistical significance of deviations in the mean values of series of long-term contrast phases of hydrological characteristics, the boundaries of which were determined using the cumulative deviation curve.

3.2. Estimation of the Exceedance Probability of River Low-Flow and High-Flow Years

Low-flow years were defined as those in which the average seasonal (summer–autumn, winter low-water, and snowmelt flood) and annual runoff were equal to or lower than the runoff corresponding to 75% exceedance probability. Conversely, high-water years were defined as those with flows equal to or greater than the values corresponding to 25% exceedance probability [27]. Years between these two brackets were deemed medium-flow years [6].

The exceedance probability of the runoff of the rivers under consideration was calculated using empirical exceedance probability curves constructed from long-term time series of the rivers' average seasonal (snowmelt flood, summer–autumn, winter) and average annual water discharge values.

Empirical values of the exceedance probability were calculated using the following formula [15]:

$$PQ_i = \left(\frac{m_i}{n+1} \right) \cdot 100\%, \quad (2)$$

where m_i is the rank position of the year in the time series of water discharge values in descending order, and n is the total number of water discharge values in the time series.

4. Results

4.1. Long Phases of Seasonal and Annual Water Flow

Two main long-term (lasting several decades) quasi-synchronous phases were revealed during the 80-year series for both the annual runoff and the runoff of each hydrological season. First, a phase of decreased runoff was observed, which was replaced by a phase of increased runoff under modern global warming (Figure 2). The years of transition to the phase of increased runoff associated with global warming for the annual and seasonal runoff were different for the rivers. The change in contrasting runoff phases on each of the rivers occurred, as a rule, in the 1980s and 1990s. The earliest and latest changes in contrasting phases were identified at the Lena–Tabaga gauge. For snowmelt flood runoff, the transition occurred in 1977/1978, and for summer–autumn runoff, it occurred in 2003/2004. Two contrasting phases (one of decreased runoff; another of increased runoff) on each of the rivers are most clearly distinguished for winter runoff. For the Lena River across Kyusyur and the Aldan, a change in contrasting winter runoff phases occurred in the 1980s–1990s, and, for the Lena across Tabaga, it occurred in the late 1990s. It should be noted that two long-term contrasting phases (one of decreased and another one of increased runoff) were also identified for snowmelt flood runoff, summer–autumn runoff, and annual runoff for the Lena across Tabaga, as well as for summer–autumn and annual

runoff for the Lena across Kyusyur. Two phases of increased runoff and two phases of decreased runoff were identified for snowmelt flood runoff in the Lena across Kyusyur, and for the snowmelt flood, summer–autumn, and annual runoff in the Aldan. In some cases, relatively short phases (a little less than 10 years) of contrasting runoff were observed against the background of long phases of decreased/increased runoff, which were included in the longer phases.

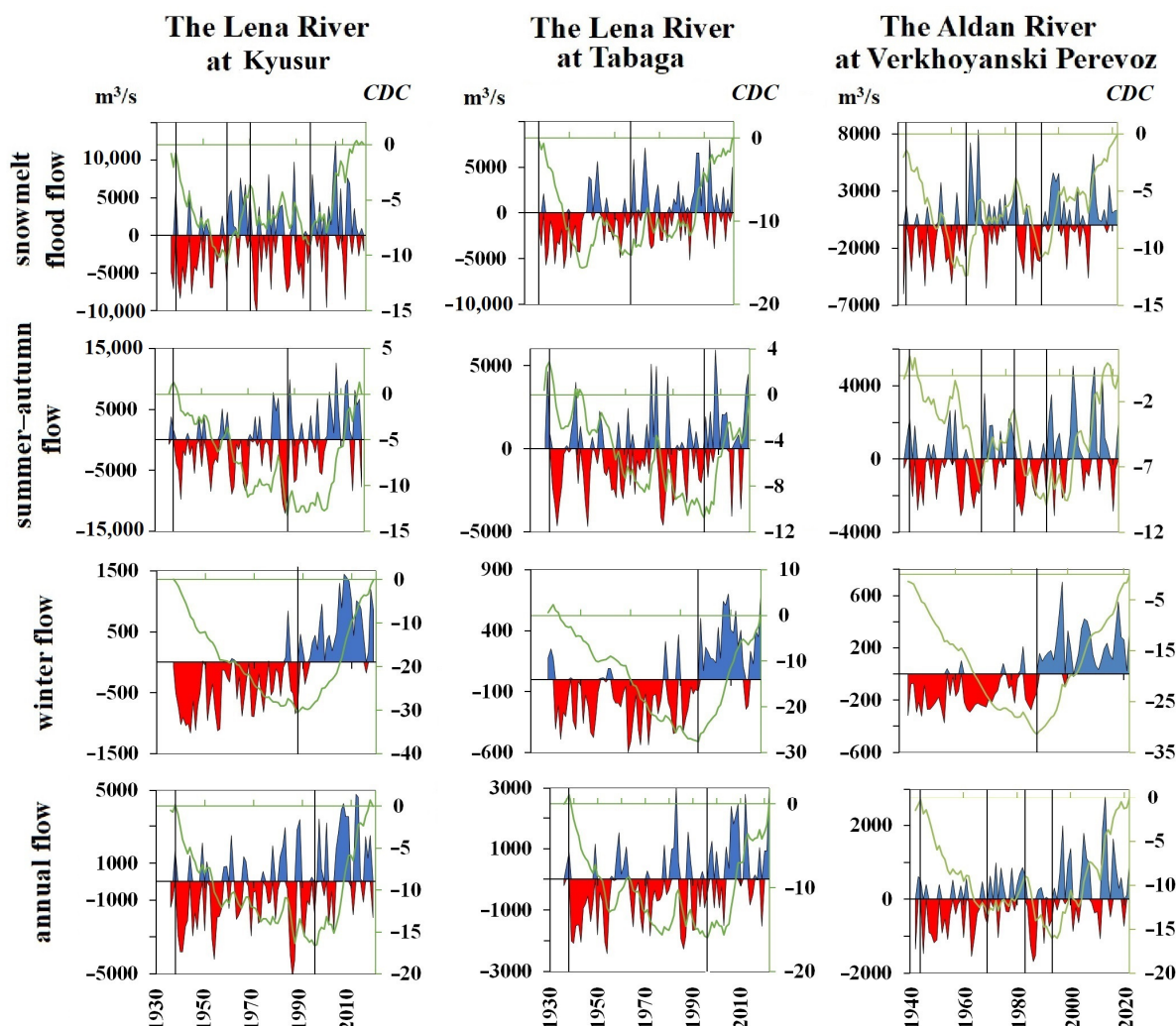


Figure 2. Long-term changes in snowmelt flood flow, summer–autumn water flow, winter water flow, and annual water flow in the Lena River across Kyusyur, the Lena River across Tabaga and the Aldan River in Verkhoyanski Perevoz. Blue and red fields indicate positive and negative deviations relative to long-term averages, respectively; the green line is the normalized cumulative deviation curve (CDC). The vertical black lines show phase boundaries (shift points) between increased or decreased values of the water flow [6].

4.1.1. Transition Years of Long Phases of Contrasting Annual and Seasonal River Water Flow

The years of phase change of contrasting annual and seasonal runoff identified using cumulative deviation curves are confirmed by estimates of the statistical significance of the differences in their mean values, determined using nonparametric criteria (Table 3). Only in a few cases were differences noticeable, particularly for the Lena snowmelt flood runoff across Tabaga.

Table 3. Shift points for contrasting phases of annual and seasonal river water flow in the Lena River across Kyusyur, the Lena River across Tabaga and the Aldan River in Verkhoyanski Perevoz.

Method	River Gauge Station					
	Lena Across Kyusyur		Lena Across Tabaga		Aldan in Verkhoyanski Perevoz	
	Shift Point	<i>p</i> Value	Shift Point	<i>p</i> Value	Shift Point	<i>p</i> Value
Snowmelt flood flow						
CDC	D→I 1960/1961 I→D 1970/1971 D→I 1996/1997	-	D→I 1977/1978	-	D→I 1965/1966 I→D 1984/1985 D→I 1994/1995	-
MWP test	1961 1971 1997	0.01 ~0.05 ~0.1	1994	0.01	1966 1985 1997	0.01 0.05 0.05
Summer–Autumn flow						
CDC	D→I 1987/1988	-	D→I 2002/2003	-	D→I 1971/1972 I→D 1983/1984 D→I 1995/1996	-
MWP test	1988	0.05	1997	0.05 (0.031)	1972 1984 1996	0.05 0.05 0.1
Winter water flow						
CDC	D→I 1987/1988	-	D→I 1997/1998	-	D→I 1989/1990	-
MWP test	1989	0.01	1994	0.01	1990	0.01
Annual water flow						
CDC	D→I 1996/1997	-	D→I 1996/1997	-	D→I 1969/1970 I→D 1983/1984 D→I 1993/1994	-
MWP test	1996	0.01	1997	0.01	1970 1984 1996	0.01 0.05 0.05

Note(s): I—increased river runoff and D—decreased river runoff, with the arrows showing the direction of runoff shift.

4.1.2. Characteristics of Contrasting Phases of Water Flow

The total duration of the decreased annual and seasonal runoff phases in the Lena across Kyusyur and Tabaga appreciably exceeds the increased runoff phase duration (except for the snowmelt flood runoff across Tabaga, for which it is virtually identical) (Table 4). The maximum duration of the decreased runoff phase is 58 years (for Lena–Tabaga, for annual runoff), and the minimum is 24 years (for Lena–Kyusyur, also for annual runoff). In the Aldan River, on the other hand, the increased runoff phase is longer than the decreased runoff phase (for the snowmelt flood runoff and annual runoff). For summer–autumn runoff, it did not differ, and only for winter runoff did the decreased runoff phase last longer than the increased runoff phase.

The most significant flow difference (as a percentage of the phase of decreased flow) for contrasting phases was revealed for winter flow. It ranges from 40% (Lena–Tabaga) to more than 76% (Aldan). For summer–autumn runoff, it varies within 18–24%, while for snowmelt flood runoff, the range is within 11–22%, and for annual runoff, the range is within 14–19%.

Table 4. Characteristics of contrasting phases of water flow of the Lena River across Kyusyur, the Lena River across Tabaga and the Aldan River in Verkhoyanski Perevoz.

River Gauge	Lena Across Kyusyur		Lena Across Tabaga		Aldan in Verkhoyanski Perevoz	
Long Phase	Mean Water Discharge, m ³ /s	Length of Phase/Years	Mean Water Discharge, m ³ /s	Length of Phase/Years	Mean Water Discharge, m ³ /s	Length of Phase/Years
Snowmelt flood flow						
D	38,081	1939–1960/22	16,004	1936–1977/42	13,452	1944–1965/22
D	39,372	1971–1996/26	–		12,882	1985–1994/10
D _{average}	38,780				13,274	
I	44,275	1961–1970/10	18,106	1978–2022/45	16,249	1966–1984/19
I	42,578	1997–2019/23	–		16,052	1995–2022/28
I _{average}	43,092				16,132	
I _{average} – D _{average} , m ³ /s	4312		2102		2858	
I _{average} – D _{average} relative to D _{average}	11.1%		13.1%		21.5%	
Summer–Autumn flow						
D	21,379	1939–1987/49	8774	1939–2003/65	7161	1945–1971/27
D	–		–		6671	1984–1995/12
D _{average}					7010	
I	25,169	1988–2019/32	10,559	2004–2022/19	8844	1972–1983/12
I	–		–		8607	1996–2022/27
I _{average}					8680	
I _{average} – D _{average} , m ³ /s	3790		1784		1670	
I _{average} – D _{average} relative to D _{average}	17.7%		20.3%		23.8%	
Winter flow						
D	2228	1937–1987/51	1251	1939–1997/59	497	1944–1989/46
I	3246	1988–2019/32	1750	1998–2022/25	878	1990–2022/33
I _{average} – D _{average} , m ³ /s	1017		499		382	
I _{average} – D _{average} relative to D _{average}	45.6%		39.9%		76.8%	
Annual flow						
D	16,493	1939–1995/57	6924	1939–1996/58	4977	1945–1969/25
D	–		–		4805	1984–1993/10
D _{average}	–		–		4928	
I	18,785	1996–2019/24	8083	1997–2022/26	5735	1970–1983/14
I	–		–		5957	1994–2022/29
I _{average}					5885	
I _{average} – D _{average} , m ³ /s	2293		1159		957	
I _{average} – D _{average} relative to D _{average}	13.9%		16.7%		19.4%	

Note(s): Abbreviations for I and D are the same as in Table 3. In the table, the symbol ‘–’ means that phases have not been revealed.

For the Lena near Kyusyur, Lena near Tabaga, and Aldan near Verkhoyansk Perevoz, changes in the standard error of mean runoff for the contrasting phases were within single-digit percentages. For snowmelt flood runoff, the values were 2.2–2.7 (2.3–3.1), 2.7–2.8 (3.0–3.8), and 2.9–5.1 (3.1–5.8), respectively. For summer-autumn runoff, they were 3.2–4.0 (4.8), 4.2–7.5 (5.1–7.7), and 4.4–5.9 (4.9–8.9). For winter runoff, they were 1.5–2.9 (2.3–5.5), 2.2–2.8 (2.9–4.7), and 3.6–6.9 (5.0–7.9). For annual runoff, they were 1.6–2.6 (3.0–3.4), 2.2–3.1 (3.3–3.6), and 2.6–4.9 (2.9–6.6). Values in parentheses account for autocorrelation. The

standard errors of the mean runoff estimates for the increased and decreased runoff phases were several times smaller than the differences between the phase means, especially for winter runoff. Accounting for autocorrelation [15] produced only a moderate increase in standard errors.

When more than one increased or decreased runoff phase was detected during the observation period (Table 4), the differences among their mean values were much smaller than—or, for short phases, comparable to—the standard error. In these cases, mean runoff was calculated for the full period that included the corresponding increased or decreased phases.

4.2. The Difference in the Frequency of Extreme Runoff Years in the Long Phases of Contrasting Water Flow

During the longest phases of increased flow (caused by modern global warming) compared to the decreased flow phases in each of the rivers, both for the annual flow and for the flow of the main hydrological seasons, there is a significant increase in the proportion of high-water years (Figure 3, Table A1). The most noticeable increase in the proportion of high-flow years was found for winter runoff, increasing from 2–5% to 27–64%, while, on the contrary, for low-flow years, it decreases from 36–41% to 0–3%. The proportion of high-flow and low-flow years changed in similar proportions during contrasting phases in the three considered rivers for snowmelt flood, the summer–autumn period, and annual runoff. Moreover, the proportion of years with runoff in the range corresponding to 25–75% exceedance probability remained relatively constant, with the exceptions of the winter runoff of the three rivers and the annual runoff of the Aldan.

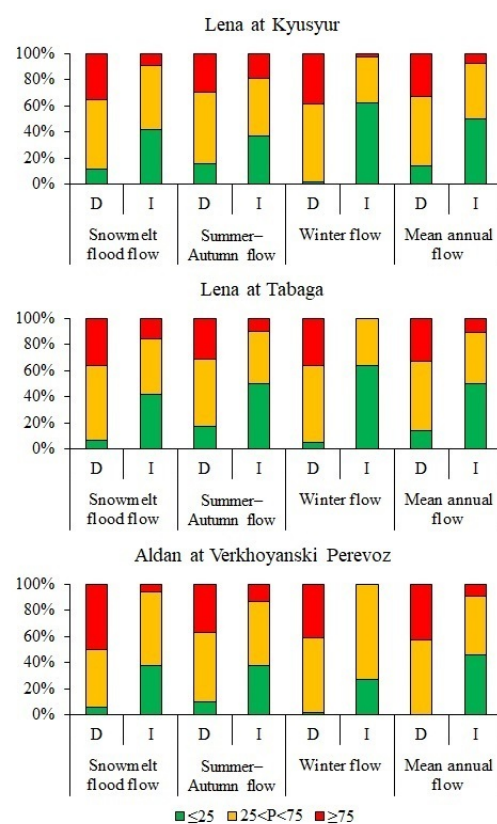


Figure 3. The proportion of low-water and high-water years (with exceedance probability ≥ 75 and $\leq 25\%$, respectively) in long-lasting phases of increased (I) and decreased (D) annual water flow.

5. Discussion

Studies show that modern global warming is causing differently directed changes in both annual and seasonal runoff over the world [3,5–7,12]. Russia and southern Africa have been studied in the most detail in this regard, and noteworthy results have also been obtained for other regions [3,4,10,11].

Although a number of results have already been obtained regarding the typification of long-term dynamics of long phases of contrasting runoff for some regions [6], as well as at the global level [27], there is an obvious need for further study in this direction, covering a diversity of territories both at the level of large regions of the world and at the global level, taking into account the accumulated long-term data and available methodological experience.

Our experience [7] shows that, as a rule, water flow characteristics exhibit statistically significant linear increase (or decrease) trends, as determined by the Mann–Kendall and Spearman tests, and linear regression. A statistically significant linear trend during the entire observation period under review is usually detected in the presence of at least two long-term contrasting phases [28,29]. At the same time, often there is no noticeable increasing (or decreasing) trend during the phase of decreased or increased runoff. Thus, taking phases into account when calculating the characteristics of river flow and other hydrological components allows us to obtain additional information about the nature of their long-term changes. Therefore, in recent years, when analyzing multi-year variability, both linear trends and long-lasting phases have been considered [28,29].

The climatic conditions of long-term phases of decreased/increased runoff have been insufficiently studied. Some features of these conditions (air temperature, precipitation, macroscale atmospheric circulation, permafrost thawing) have been identified for a number of Arctic rivers: Northern Dvina, Pechora, Ob, Yenisei, Lena, etc. [6,30,31].

However, research on determining the initial boundary of the period of modern global warming in different regions and the degree of its conjugation with the boundaries of the change in long-lasting phases of contrasting runoff during this period remains insufficient.

Methods for detecting abrupt changes (shift points) in the mean, variance, and frequency structure have been developed and are widely used [16,32]. Various statistical packages include such tests [26]. New methods are also being developed, such as the robust regime-shift detection algorithm for water-flow dynamics [33]. Although brief summaries of these methods are available, the authors are not aware of any detailed comparison of their application to long-term flow changes in rivers with different water regimes.

The relationship between the frequency of low- and high-water flow years and the nature of prolonged water flow phases also remains poorly understood. The results obtained show that alternating prolonged periods of increased/decreased flow are closely linked to significant changes in the frequency of low- and high-flow years. This can bring about significant, including negative, impacts on both ecosystems and human activities, which have adapted to these conditions over a long period of time.

6. Conclusions

We revealed how long phases of decreased/increased flow are related to the frequency of years with abnormally low water (when the water flow was less or equal to 75% exceedance probability levels) and high-water years (when the water flow was higher or equal to 25% exceedance probability levels) on the Lena River across Kyusyur and Tabaga, as well the Aldan River in Verkhoyanski Perevoz (the Lena's right tributary), for periods starting from the 1930s and 1940s.

Two main quasi-synchronous phases were revealed over the 80-year observation time series for both annual flow and the flow of each hydrological season (with phases lasting

several decades). Initially, this was a phase of decreased flow, which was replaced by a phase of increased flow during the current period of global warming.

The phase-transition years corresponding to increased runoff associated with global warming for annual runoff and the runoff of the main hydrological seasons of the year varied among the gauge stations, but typically, these years occurred in the 1980s and 1990s. The earliest and latest changes in contrasting phases in the Lena–Tabaga were identified for snowmelt flood runoff (1977/1978) and summer–autumn runoff (2003/2004). Two contrasting phases are most clearly distinguished for winter runoff for each of the rivers. For the Lena across Kyusyur and for the Aldan, the change in contrasting phases of winter runoff occurred in the 1980s–1990s, while for the Lena across Tabaga, they occurred in the late 1990s.

The years of long phase change regarding contrasting annual and seasonal runoff identified using cumulative deviation curves are, in most cases, confirmed by estimates of the statistical significance of the differences in their mean values, determined using the Student and Mann–Whitney–Pettit tests. Only in a few cases were differences in the results noticeable, particularly for the Lena snowmelt flood runoff across Tabaga.

The total duration of the low-flow phases of annual and seasonal flow in the Lena River across Kyusyur and Tabaga appreciably exceeds the duration of the snowmelt flow phases (except for the snowmelt flood flow across Tabaga, where it is virtually identical). The maximum duration of the low-flow phase is 58 years (for the Lena–Tabaga (annual flow)), and the minimum is 24 years (for the Lena–Kyusyur (annual flow)). On the other hand, for the Aldan, the duration of the increased flow phase exceeds the duration of the decreased flow phase (for snowmelt flood and annual runoff). For summer–autumn runoff, it is the same, and only for winter runoff is the decreased flow phase longer than the increased flow phase.

The most significant flow differences (as a percentage of the phase of decreased flow) for contrasting phases were revealed for winter flow. It ranges from 40% (Lena–Tabaga) to more than 76% (Aldan). For summer–autumn runoff, it ranges within 18–24%, while for snowmelt flood runoff, the range is 11–22%, and for annual runoff, the range is 14–19%.

The standard error of the mean runoff estimates for the compared increased and decreased runoff phases were several times smaller than the differences between the phase means, especially for winter runoff. Accounting for autocorrelation substantially increased the standard error in some cases. The largest relative differences in the frequency of abnormal years between contrasting runoff phases occurred in winter. In other seasons and for the year as a whole, except for the Aldan River, these differences were less pronounced.

In the Lena near Kyusyur, the proportion of high-water years varied from 37% (summer–autumn runoff) to 62% (winter runoff) in the phase of increased runoff and from 2% (winter runoff) to 16% (summer–autumn runoff) in the phase of decreased runoff.

In the Lena across Tabaga, it varied from 42% (snowmelt flood runoff) to 64% (winter runoff) in the increased flow phase and from 5% (winter runoff) to 14% (annual runoff) in the decreased runoff phase.

In the Aldan in Verkhoyansky Perevoz, it varied from 27% (winter runoff) to 46% (annual runoff) in the phase of increased flow and from 0% (annual runoff) to 10% (summer–autumn runoff) in the phase of decreased flow.

Author Contributions: A.G.G. developed the research concept and methodology and analyzed the results of the calculations; A.G.G. and E.A.B. made the main contributions to the preparation of this manuscript; I.P.M., E.A.B., O.O.B. and Y.Y.A. contributed to the calculation; P.Y.G. reviewed and edited the English version of this manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The article is based on the results of studies that were carried out under the Governmental Order of the Institute of Geography, Russian Academy of Sciences, state assignment FMWS-2026-0003, (1025030300154-4). The work of Pavel Groisman is partially supported by the U.S. NSF Grants # 2020404 ‘Belmont Forum Collaborative Research: Coastal Ocean Sustainability in Changing Climate’ and # 2127343 ‘NNA Collaborative Research: Frozen Commons: Change, Resilience and Sustainability in the Arctic’ and by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES4320002.

Data Availability Statement: The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: Pavel Y. Groisman was employed by the Hydrology Science and Services Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

USSR Union of Soviet Socialist Republics
 CDC Cumulative deviation curve
 MWP Mann–Whitney–Pettitt test

Appendix A

Table A1. The proportion of low-water and high-water years (with exceedance probability ≥ 75 and $\leq 25\%$ of probability of exceedance) in long-lasting phases of increased and decreased annual and seasonal water flow in the Lena River across Kyusyur and Tabaga, as well as the Aldan River in Verkhoyanski Perevoz.

Phase	Lena Across Kyusyur		Lena Across Tabaga		Aldan in Verkhoyanski Perevoz	
	$\geq 75\%$	$\leq 25\%$	$\geq 75\%$	$\leq 25\%$	$\geq 75\%$	$\leq 25\%$
Snowmelt flood flow						
D	1939–1960 1971–1996		1936–1977		1944–1965 1985–1994	
	35	12	36	7	50	6
I	1961–1970 1997–2019		1978–2022		1966–1984 1995–2022	
	9	42	16	42	6	38
Summer–Autumn flow						
D	1939–1987		1939–2002		1945–1971 1984–1995	
	30	16	31	17	37	10
I	1988–2019		2003–2022		1972–1983 1996–2022	
	19	37	10	50	13	38
Winter flow						
D	1937–1987		1939–1997		1944–1989	
	39	2	36	5	41	2

Table A1. Cont.

Phase	Lena Across Kyusyur		Lena Across Tabaga		Aldan in Verkhoyanski Perevoz	
	≥75%	≤25%	≥75%	≤25%	≥75%	≤25%
I	1988–2019		1998–2022		1990–2022	
	3	62	0	64	0	27
Annual flow						
D	1939–1995		1939–1996		1945–1969 1984–1993	
	33	14	33	14	43	0
I	1996–2019		1997–2022		1970–1983 1994–2022	
	8	50	11	50	9	46

References

- Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2023; p. 3056. [\[CrossRef\]](#)
- Reid, P.C.; Hari, R.E.; Beaugrand, G.; Livingstone, D.M.; Marty, C.; Straile, D.; Barichivich, J.; Goberville, E.; Adrian, R.; Aono, Y.; et al. Global impacts of the 1980s regime shift. *Glob. Change Biol.* **2016**, *22*, 682–703. [\[CrossRef\]](#) [\[PubMed\]](#)
- Alemaw, B.; Chaoka, T. Trends in the flow regime of the southern African rivers as visualized from rescaled adjusted partial sums (RAPS). *Afr. J. Sci. Technol.* **2002**, *3*, 70–79. [\[CrossRef\]](#)
- Đurin, B.; Raič, M.; Sušilović, P. Analysis of homogeneity and isotropy of the flow in the watercourses by applying the RAPS and IPTA methods. *Adv. Civ. Archit. Eng.* **2024**, *15*, 67–83. [\[CrossRef\]](#)
- Georgiadi, A.G.; Groisman, P.Y. Long-term changes of water flow, water temperature and heat flux of two largest arctic rivers of European Russia, Northern Dvina and Pechora. In *Environmental Research Letters*; IOP Publishing: Bristol, UK, 2022; Volume 17, pp. 1–14.
- Georgiadi, A.G.; Groisman, P.Y. Extreme low flow during long-lasting phases of river runoff in the central part of the East European Plain. *Water* **2023**, *15*, 2146. [\[CrossRef\]](#)
- Georgiadi, A.G.; Kashutina, E.A.; Milyukova, I.P. Long-term changes of water flow, water temperature and heat flux of the largest Siberian rivers. *Polarforschung* **2018**, *87*, 167–176. [\[CrossRef\]](#)
- Georgiadi, A.G.; Milyukova, I.P. Peculiarities of long-term phases of the increased and decreased Don and Lena runoff in the 19th–21st centuries. *Russ. Meteorol. Hydrol.* **2023**, *48*, 1066–1075. [\[CrossRef\]](#)
- Georgievsky, V.Y. *Scientific and Applied Reference Book: Long-Term Characteristics of Water Inflow into the Largest Reservoirs of the Russian Federation*; Georgievsky, V.Y., Ed.; OOO APC Ofort: Moscow, Russia, 2017; p. 132, ISBN 978-5-9907194-5-3. (In Russian)
- Sharma, S.; Singh, P.K. Long term spatiotemporal variability in rainfall trends over the state of Jharkhand, India. *Climate* **2017**, *5*, 18. [\[CrossRef\]](#)
- Yeh, C.-F.; Wang, J.; Yeh, H.-F.; Lee, C.-H. Spatial and temporal streamflow trends in Northern Taiwan. *Water* **2015**, *7*, 634–651. [\[CrossRef\]](#)
- Shi, X.; Qin, T.; Nie, H.; Weng, B.; He, S. Changes in major global river discharges directed into the ocean. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1469. [\[CrossRef\]](#) [\[PubMed\]](#)
- Muraveisky, S.D. *Rivers and Lakes, Hydrobiology, Runoff*; Geografiz: Moscow, Russia, 1960; p. 387. (In Russian)
- Cramer, H. *Mathematical Methods of Statistics*; Princeton University Press: Princeton, NJ, USA, 1946; p. 575.
- Georgievsky, V.Y. *Determination of the Main Design Hydrological Characteristics*; Rules Summary: Moscow, Russia, 2023; p. 103. (In Russian)
- Kundzewicz, Z.W.; Robson, A.J. Change detection in hydrological records—A review of the methodology. *Hydrol. Sci. J.* **2004**, *49*, 7–19. [\[CrossRef\]](#)
- Rodionov, S.N. A sequential algorithm for testing climate regime shifts. *Geophys. Res. Lett.* **2004**, *31*, L09204. [\[CrossRef\]](#)
- Frolova, N.L.; Magritskii, D.V.; Kireeva, M.B.; Grigor'ev, V.Y.; Gelfan, A.N.; Sazonov, A.A.; Shevchenko, A.I. Streamflow of the Russian rivers under current and forecasted climate changes. A review of publications. 1. Assessment of changes in the water regime of Russian rivers by observation data. *Water Resour.* **2022**, *49*, 333–350. [\[CrossRef\]](#)

19. Shuttle Radar Topography Mission. Available online: <https://www.earthdata.nasa.gov/data/instruments/srtm> (accessed on 12 January 2026).
20. ArcAtlas: Our Earth. Environmental Systems Research Institute (1996). Inc. and DATA+ All Rights Reserved. Available online: https://geo2.scholarsportal.info/#r/details/_uri@=1952603239 (accessed on 12 January 2026).
21. Circum-Arctic Map of Permafrost and Ground-Ice Conditions. (GGD318, Version 2). Available online: <https://nsidc.org/data/ggd318/versions/2> (accessed on 12 January 2026).
22. Barabanova, E.A. Comparison of reservoirs by the complex of their positive and negative impacts on the environment and economy. *Izv. Akad. Nauk. Ser. Geogr.* **2004**, *2*, 72–82. (In Russian)
23. Kalinin, G.P.; Milyukov, P.I. Approximate Calculation of Unsteady Motion of Water Masses. *Proc. Cent. Inst. Forecast.* **1958**, *66*, 72. (In Russian)
24. Andreyanov, V.G. Cyclical fluctuations of annual runoff and their accounting in hydrological calculations problems of runoff calculations. *Proc. State Hydrol. Inst.* **1959**, *68*, 3–50. (In Russian)
25. Pettitt, A.N. A non-parametric approach to the change-point problem. *J. R. Stat. Soc.* **1979**, *28*, 126–135. [[CrossRef](#)]
26. Štěpánek, P. AnClim and ProClimDB Software for Data Quality Control and Homogenization of Time Series. Geophysical Research Abstracts Vol. 17, EGU2015-15570, 2015 EGU General Assembly 2015. Available online: <https://meetingorganizer.copernicus.org/EGU2015/EGU2015-15570.pdf> (accessed on 10 December 2025).
27. Kuzin, P.S.; Babkin, V.I. *Geographical Patterns of the Hydrological Regime of Rivers*; Gidrometeoizdat: Leningrad, Russia, 1979; p. 200. (In Russian)
28. Magritsky, D.V.; Frolova, N.L.; Vasilenko, A.N. The Inflow of River Water into Russian Arctic Seas: Its Amount, Long-term and Intraannual Changes. *Russ. Meteorol. Hydrol.* **2025**, *50*, 369–381. [[CrossRef](#)]
29. Xi, Y.; Su, Y.; Yang, H.; Luo, Z.; Pan, G.; Xu, L.; Li, Z. Significant Increases in Extreme Heat and Precipitation over the Past 62 Years in the Tarim River Basin and Their Large-Scale Climatic Drivers. *Sustainability* **2026**, *18*, 2787. [[CrossRef](#)]
30. Georgiadi, A.G.; Kashutina, E.A. The Features of Long-Term Annual and Seasonal Runoff Changes for Lena Basin Rivers. *Izv. Akad. Nauk. Ser. Geogr.* **2014**, *2*, 71–83. (In Russian)
31. Georgiadi, A.G.; Kashutina, E.A. Long-Term Runoff Changes of the Largest Siberian Rivers. *Izv. Akad. Nauk. Ser. Geogr.* **2016**, *5*, 70–81. (In Russian) [[CrossRef](#)]
32. Rodionov, S.N. A brief overview of the regime shift detection methods. Methods for detecting regime shifts in large marine ecosystems: A review with approaches applied to North Pacific data. *Progr. Oceanog.* **2005**, *60*, 165–182.
33. Dastour, H.; Gupta, A.; Achari, G.; Hassan, Q.K. A Robust Regime Shift Change Detection Algorithm for Water-Flow Dynamics. *Water* **2023**, *15*, 1571. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.