The dominant source and volume of highest river floods have shifted in Finland and northern Russia.

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We analyzed observations on floods in rivers located in Finland and northern Russia where hazardous floods often happen during a spring flooding period. We evaluated the length of spring flooding periods, the volume of spring floods, the yearly maximum water discharges (annual floods) and their dates from hydrographs. The hydrographs were evaluated using the daily water discharges given in yearly books published by the national hydrological services. The long term time series of annual and spring floods were used to define shifts (step changes) by applying the moving window technique. Three statistical criteria namely the Student test, the Kolmogorov-Smirnov test and the Mann-Whitney test were used. Our results suggest that the annual floods were recorded in the spring flooding period in more than 85 % of the rivers selected. In the last two decades, the number of annual floods that happened in autumn-winter season increased almost twice in the southern Finnish rivers. The melting snow remains the dominant source for the highest floods in the rivers located in northern Finland and Russia. The step changes were defined in half of the time series of the annual floods and spring floods. In over a one-third of the records of the spring floods, the step changes dated to the late 1990s, since then the volume of floods increased by 21 % on average. The step changes in the records of the annual floods dated to the early 1950s, mid 1970s and early 1990s.

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Key Points:

- In Finland and northern Russia, over 32–53 % of annual river flow passes during the spring flooding period may last 43-97 days.
- In the past two decades, winter rains have become the dominant source for the annual floods in the rivers located in southern Finland.
- The shifts were detected in 45% of the records on the annual and/or spring floods that happened to rivers in Finland and northern Russia.

Keywords: climate, river floods, hydrological regime, shifts, extremes, cold regions

Abstract

We analyzed observations on floods in rivers located in Finland and northern Russia where hazardous floods often happen during a spring flooding period. We evaluated the length of spring flooding periods, the volume of spring floods, the yearly maximum water discharges (annual floods) and their dates from hydrographs. The hydrographs were evaluated using the daily water discharges given in yearly books published by the national hydrological services. The long term time series of annual and spring floods were used to define shifts (step changes) by applying the moving window technique. Three statistical criteria namely the Student test, the Kolmogorov-Smirnov test and the Mann-Whitney test were used. Our results suggest that the annual floods were recorded in the spring flooding period in more than 85 % of the rivers selected. In the last two decades, the number of annual floods that happened in autumn-winter season increased almost twice in the southern Finnish rivers. The melting snow remains the dominant source for the highest floods in the rivers located in northern Finland and Russia. The step changes were defined in half of the time series of the annual floods and spring floods. In over a one-third of the records of the spring floods, the step changes dated to the late 1990s, since then the volume of floods increased by 21 % on average. The step changes in the records of the annual floods dated to the early 1950s, mid 1970s and early 1990s.

Plain Language Summary

River floods are among well known hazards in Europe damaging social infrastructure including roads. In Finland and northern Russia, the highest floods in rivers have been observed during a spring flooding period, and snow melt is a dominant source of these floods. We further investigated whether dominant sources and magnitude of highest river floods have changed during an observational period? Our results show that in the last two decades, rains have become an essential source to form the highest floods that happen to rivers located south of Finland. In the northern Finland, the snow melt is the dominant source for the highest river floods. The snow-sourced floods have become larger in volume since the early 1990s in 36–45 % of rivers located in northern Finland and Russia. It may require a new evaluation of the flood-related risks for the road infrastructures in these regions.

1 Introduction

Floods are among well known hazards; the river floods are natural events that become “extreme” if only they are dangerous for a social infrastructure. The extreme floods (also known as design floods) are needed while building roads, bridges, pipelines, dams and houses. The engineering hydrology defines the extreme floods statistically as events that happen once a 10, 50, 100, … 1000 years. The extreme floods are estimated from observations at sites in rivers and with statistical methods (ie. frequency analysis) or from modeling (WMO-168, 2009; Benson, 1968). The extreme floods are evaluated from the hydrological records on yearly maximum flood (highest peak water discharge in a year or annual flood) assuming no change in climate and hydrological regime happen in the future (Ashkar et al., 1988). The fact of the change does not allow extrapolating the river flood-related risks for roads, bridges and dams to the future (Milly et al., 2008; Kundzewicz et al., 2008; Madsen et al., 2013).

The climate is defined by a set of statistical estimators (ie. mean, median, percentiles) calculated from observations of the meteorological variables lasting a n-years period (Monin, 1986). The length of the period is often 30 years and these (“climatological”) periods are suggested by the World Meteorological Organization (WMO). Then, the one-two statistical estimates (moments) are evaluated for the climatological periods (ie. 1961-1990, 1991-2020 or 1970-2000). These periods are not necessarily linked to the periods when no statistically significant trends or step-changes are found in the observed hydrological series.

To define the hydrological regime, up to four statistical estimators (moments) are evaluated from the hydrological records applying methods from the extreme value (frequency) analysis (Sokolovskiy, 1968; WMO-168, 2009). In the frequency analysis, the probability of floods that rarely happen or not recorded in a history of instrumental observations (the extreme or design floods) are evaluated from the exceedance probability distributions. The engineering hydrology accepts the various skewed distributions, and the Pearson’s distributions are among others (Bulletin-17B, 1982; SP33-101-2003, 2004); to their contractions, up to four moments are needed to be known whether from observations or models (Sokolovskiy, 1968). The length of the observational period is crucial for the accuracy of the highest moments; only few records allow evaluation of the third statistical moment with an acceptable accuracy (Rozhdestvenskiy and Chebotarev, 1974).

The extreme floods in rivers are evaluated from the records of a yearly maximum water discharge observed in rivers; it is also known as the annual flood (WMO-385, 2012). Henceforth, we used this term to mention the yearly maximum water discharge. The annual floods have originated from various sources (natural and man-made), and their dominant source depends on the climate, river catchment properties and artificial regulation (Whitfield, 2012). In southern European rivers, the heavy rains, rain-on-snow events and dam failures are typical sources for the annual floods (Hall et al.; 2014). In northern Europe, the annual floods are often sourced by the snow (or/and ice) melt (Snorrason et al., 2000; Kaluzhny and Lavrov, 2012; Hodgkins et al., 2017); and they happen in the spring flooding period which does not coincide with a calendar spring lasting from March to May (Jónsdóttir et al., 2006; Hyvärinen and Puupponen, 1986). The dominant source of the annual floods in rivers changes toward a time (Whitfield, 2012; Bennet et al., 2015).

In changing hydrological regimes, the design floods cannot be evaluated only from the historical records; and the extreme floods are predicted using hydrological models (Madsen et al., 2013; Cherry et al., 2017). The conceptual process-based hydrological models simulate the river water discharge series (daily or sub-daily) from meteorological variables (precipitation and air temperature) given in forecasts. The conceptual hydrological models are run on a catchment scale on semi-distributed and distributed types (Beven and Kirkby, 1979; Lohmann et al., 1993; Lindström et al. 2010; Arheimer and Lindström, 2015; Donnelly et al., 2016; Hamman et al., 2018). The parameters of these hydrological models are calibrated from the observations at hydrometric sites (Hundecha et al.; 2016). The calibration includes manual tuning, and it becomes burdensome to compute the parameters for the periods with different hydrological regimes in case of a large number of catchments (Hundecha et al., 2016 and 2020). The spatial resolutions of variables given in the meteorological forecasts, their uncertainties and methods applied to set numerous parameters affect the results of the distributed hydrological models. The series of the river water discharges simulated by the conceptual hydrological models are considered as “observed records” in estimations of the extreme river floods applying methods of the frequency analysis (Benson, 1968; Bowman and Shenton, 1993; WMO-168, 2009; England et al. 2019).

The advanced frequency analysis approach offers an alternative to the conceptual hydrological models in the estimation of the extreme (design) floods in changing hydrological regimes (Kovalenko, 1993). In the advanced frequency analysis, the statistical estimators are simulated from the information given in the climate projections (Kovalenko, 2014); the time series of the river water discharges are not simulated. The methods of the approach implemented in the probabilistic hydrological models which may have up to four parameters calibrated from hydrometric observations at sites (Shevnina et al., 2017). The model’s parametrization required the estimations of three-four initial statistical moments to be known from the historical records for the periods differing in the hydrological regime (Shevnina and Silaev, 2019). The periods are divided by a year when the shifts (step-changes) are detected in the hydrological records using various statistical tests (WMO-168, 2009; Hall et al., 2014).

We analyzed the long term time series of the annual floods and volume of spring floods observed at 12 rivers we selected in Finland and northern Russia. In this region, the annual floods often happen during a spring flooding period and sourced by snow melt. We estimated the length of the spring flooding period, volume of the spring floods and timing and magnitude of the annual floods from hydrograph. Then, we analyzed the long term time series of the river floods with the statistical methods to define the year when the hydrological regimes have changed (shifted). The records with the shifts are needed for the parametrization of the probabilistic hydrological models.

2 Study area

The study focuses on the territory of Finland and northern Russia where the cold climate with cold summer and without dry season is dominated (Fig. 1 a). The annual mean temperature varied between 1.0 and 5.5 °C in central and southern Finland, and slightly less than -2 °C in northern Finland. The annual precipitation varied between 500 and 700 mm in southern and central Finland; it is about 600 mm in northern Finland, where about a half of the precipitation is snow (Jylhä et al., 2010). In northern Russia, the annual precipitation varied between 400 and 700 mm, and up to a half of the precipitation fall in a cold season lasting from October to April (Peel et al., 2007). The annual floods are often formed during the spring season due to snow melting (Hyvärinen and Puupponen, 1986; Sokolovskiy, 1968). The selected river catchments are located in northern Europe where the cold climate (subtype Df, with summer without dry season) is dominated (Fig. 1b), and in the future the climate subtype will change over the region (Fig. 1 c), and it affects the dominant source, magnitude of the extreme floods and their occurrence.

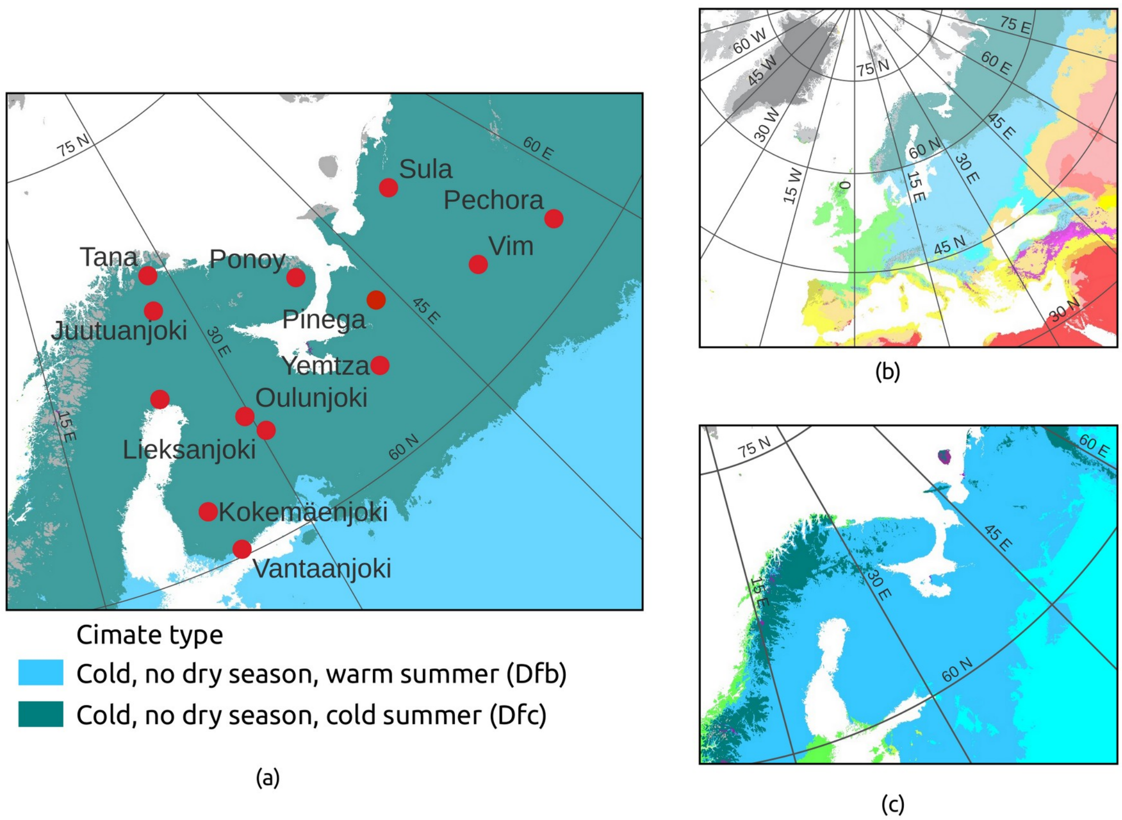


Figure 1. The location of the river catchments selected in this study: red dots indicate the location of the hydrometric sites; colors show the climate types / subtypes in the Köppen classification for the present (a, b) and the future (c) given according to Beck et al., (2018).

We selected 12 hydrometric sites that outlined the unregulated river catchments where the longest hydrometric records are published in the national hydrological books. The area of the river catchments varied from 1620 to 39000 km^2: two catchments with the area smaller than 5000 km^2, five catchments with the area between 5000 and 10000 km^2 and five catchments which are bigger than 10000 km^2. Most of the catchments are covered by the forest and tundra, or tundra mixed with swamp or wetland (Table 1).

Table 1. The location and physiography of river catchments selected in the study domain.

River – Gauge name	Lat	Observational	Catchment	Dominant land

		period / length	area, km^2	cover type(s)
Juutuanjoki – Savukkoniva	68.9	1930 – 2013 / 84	5160	Forest
Vantaanjoki – Oulunkylä	60.2	1937 – 2021 / 85	1620	Swamp
Tornionjoki – Karunki	66.0	1911 – 2021 / 111	39000	Forest
Oulujoki – Lentua, outlet	64.2	1911 – 2021 / 110	2045	Forest
Kokemäenjoki – Muroleenkoski	61.9	1863 – 2021 / 160	6102	Swamp, wetland
Lieksanjoki – Ruunaa	63.4	1931 – 2021 / 91	6260	Forest
Tana – Polmak Nye	70.1	1930 – 2018 / 89	14160	Tundra, swamp
Ponoy – Kanevka	67.1	1933 – 2020 / 88	10200	Tundra, swamp
Pinega – Kulogory	64.7	1936 – 2020 / 83	36700	Forest
Pechora – Yaksha	61.2	1936 – 2020 / 85	9620	Forest
Vim – Veslyana	63.0	1937 – 2020 / 84	19100	Forest
Sula – Kotkina	67.0	1936 – 2020 / 84	8500	Tundra

In Table 1, the area and dominant land cover types are given according to Gudmundsson et al., (2018) for the Finnish catchments, and according to the multi-year books (Yelshina and Kupriyanova, 1970; Vodogretskiy, 1972) for the catchments which are located in Russia. The numerous gaps dating to the early 1990s are in the records collected at the Russian sites.

3 Materials and Methods

The river runoff (annual, maximum, seasonal, monthly, etc) is estimated from water discharges measured at hydrometric sites. In this study, the river runoff was evaluated using (a) the daily water discharges given in the Global Runoff Data Center, GRDC dataset (https://www.bafg.de/ last access 12.01.2022); (b) the hydrological books published by the Finnish Environmental Institute (Finland) and the State Hydrological Institute (the Russian Federation); and (c) the information system for the monitoring of water bodies of the Russian Federation (https://gmvo.skniivh.ru/index.php?id=1, last access 10.10.2022).

The length of spring flooding period and volume of spring floods were evaluated from the hydrographs. The dates when the spring flooding event begins and ends were calculated as follows:

$$DYB = \left[D(t) \geq A \right] \wedge \left[T \geq B \right]$$

$$DYE = \left[D(t) < 0 \right], \left[D(t+1) > 0 \right] \wedge \left[Q \rightarrow CQ_m \right]$$

where $D(t) = Q(t-1) - Q(t)$ and $D(t+1) = Q(t-2) - Q(t)$; Q is the daily water discharge (m^3s^{-1}); T is length of the period when $D(t+1) - D(t) > 0$ (day); Q_m is the average daily water discharge in January and February; *A*, *B* and *C* are the empirical coefficients equaling 5.6, 5 and 3 as it is suggested for the river catchments located in northern Russia. These equations allow us to define the dates with the accuracy of 5-8 days; the errors inherent in the estimation of the volume of the spring flooding period do not exceed 10 % (Shevnina, 2013). The volume of flow passing the site during the spring flooding period was integrated over a period of spring flood event, and it divided to the river catchment area to express the volume in the depth of runoff (mm). We estimated how many flows pass in a spring flooding period compared to the flow passing in a year. We also estimated the date when the yearly maximum water discharge was recorded in each year, and then marked whether it happened during the spring flooding period or not.

We applied the hydrological records on the yearly maximum water discharge (annual flood) and volume of spring flood to define the periods differing in their hydrological regimes. The step changes (shifts) in the time series were evaluated with the moving window technique (Ducré-Robitaille et al., 2003; Kovalenko, 1993). In this technique, the whole period is divided into two periods: the length of the first period equals a chosen minimum, and the length of the second period equals a length of the whole period minus a chosen minimum). For two periods, the difference in the statistics is evaluated with statistical tests; then, the length of the first period is increased by 1; the calculations are repeated until the length of the second period becomes equal to the chosen minimum (Shevnina et al., 2017). With this technique, three statistical tests namely the Student test (the parametric test), the Kolmogorov-Smirnov test and the Mann-Whitney test (two non-parametric tests) were applied (Mitropolsky, 1961; Rozhdestvenskiy and Saharyuk, 1981). We used the 0.05 level of the statistical significance in defining the step changes in the time series (Rozhdestvenskiy and Chebotarev, 1974).

The probabilistic hydrological models ingest the precipitation and air temperature (averaged over n-year period) to be known from observations or climate projections (Shevnina and Silaev, 2019). The models' cross-validation procedure requires the statistical moments to be known from observed series of river runoff for two periods which were defined by the moving window technique. Then, the mean (m), the coefficient of variation (*CV*), the coefficient of skewness (*CS*) were calculated from the statistical moments (Rozdestvenskiy and Chebotarev, 1974). The uncertainties inherent in the statistical estimators were calculated with the formulas given in the Annex.

4 Results

The length of the spring flooding period and volume of spring flood were calculated from the dates when a flooding event begins (*DFB*) and ends (*DFE*) which were estimated from the daily water discharges (hydrograph). Figure 2 shows the hydrographs for two rivers where the annual floods happen during (a) a spring flooding period (as in most rivers in northern Finland and northern Russia) and (b) a winter period (as in many rivers in southern Finland). The yearly maximum water discharge (annual flood) and its date (*DFMax* in Fig. 2) were calculated, it allows us to divide the floods into two groups depending whether they happened during the spring flooding event or not.

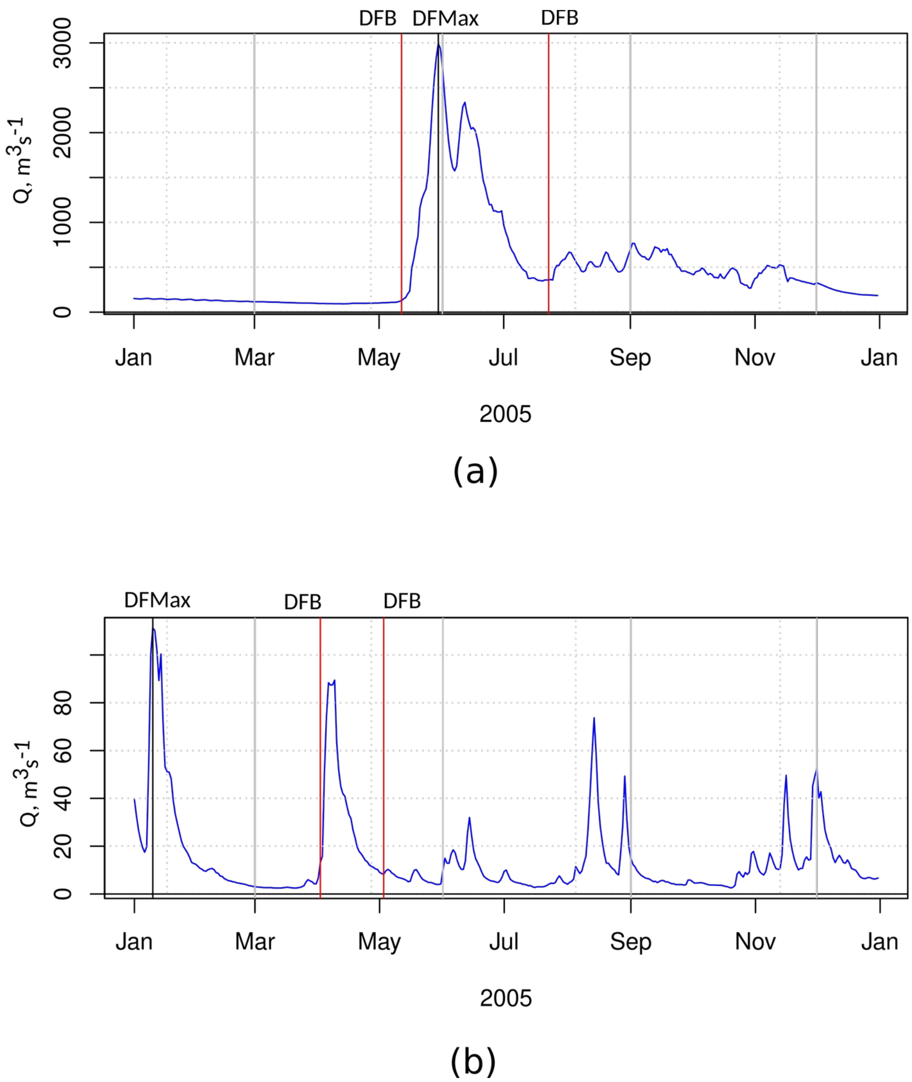


Figure 2. The dates of spring flood events begin and end (red lines) and date of the yearly maximum water discharge (black line) in Tornionjoki River at Karunki site (a) and in Vantaanjoki River at Oulunkylä site (b). The gray lines show the dates linked to the calendar seasons (winter, spring, summer and autumn).

In most rivers, the spring flooding period begins by the end of April, and it ends by June. The length of the spring flooding period varied between 43 and 97 days; the longer spring flooding period (>80 days) is estimated for the middle size river catchments located northern Finland; it is shorter than 60 days in the most northeastern Russian rivers. Table 2 shows the average for the length of the spring flooding period, the volume of the spring floods and the yearly maximum water discharges and their dates. The contribution of the spring flood flow to the annual flow varied from 32 % (Sula River) to 53 % (Pechora River); the contribution rises from the south to the north.

Table 2. The average of the volume of spring flood (*FRD*, mm), the average of the dates of spring flood begin and end (*DFB* and *DFE*), the average of the length of spring flooding period (*LFP*, day of year), the average of the maximum daily water discharge (Q_{max}, m^3s^{-1}) and its date (Df_{max}); N_s is a percent of the annual floods sourced by snow melt.

River	Spring flood			Annual flood		D_f	N_s
	DFB	*LFP*	*FRD*, mm m ± σ_m	Df_{max}	Q_{max}, m^3s^{-1} m ± σ_m		
Juutuanjoki	09.05	66	150 ± 5	26.05	315 ± 13	0.44	100
Vantaanjoki	29.03	43	87.9 ± 4	23.05	130 ± 5	0.36	72
Tornionjoki	29.04	75	158 ± 4	28.05	2210 ± 47	0.48	100
Oulunjoki	29.04	86	172 ± 4	29.05	77.4 ± 2.2	0.43	98
Kokemäenjoki	15.04	94	111 ± 3	04.06	118 ± 3	0.40	80
Lieksanjoki	24.04	97	142 ± 4	21.06	146 ± 4	0.37	85
Tana	05.03	61	188 ± 5	27.03	1569 ± 54	0.51	100
Ponoy	04.05	72	177 ± 5	24.05	702 ± 17	0.51	100
Pinega	28.04	54	191 ± 7	16.05	3269 ± 145	0.45	100
Pechora	28.04	56	273 ± 7	22.05	1446 ± 40	0.53	100
Vim	28.04	50	164 ± 5	16.06	1954 ± 79	0.46	86
Sula	06.05	56	214 ± 5	27.05	1190 ± 33	0.32	100

More than 85 % of the annual floods in the rivers were recorded during the spring flooding period. In two southernmost rivers, 20-28 % of the annual floods are recorded in the late autumn or winter periods. Figure 3 shows the number of annual floods that happened during the spring flooding period in five rivers in three different periods. We estimated this number from the hydrological records for (a) the whole observational period, (b) the period from early 1930s to 2000; and (c) the period from 2001 to 2021. In the southernmost Vantaanjoki River, the number of annual floods sourced from snow melt has decreased almost twice in the last two decades (left plot in Fig. 3); it can be said that rain has contributed essentially to form the highest floods in rivers located southern Finland. Since the 2000s, only 43 % of the annual floods were recorded during the spring flooding period in Vantaanjoki River. In the northern rivers (Oulunjoki River, Vim River), the snow melt still remains the dominant source for the annual floods.

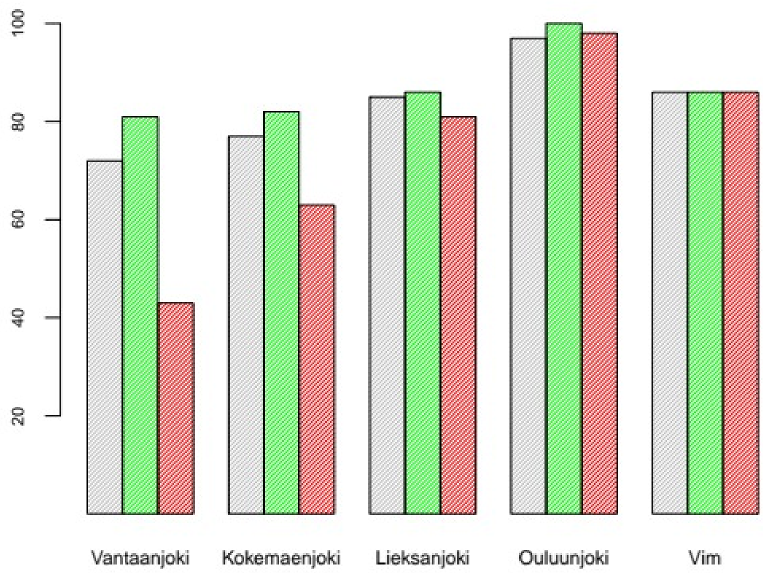
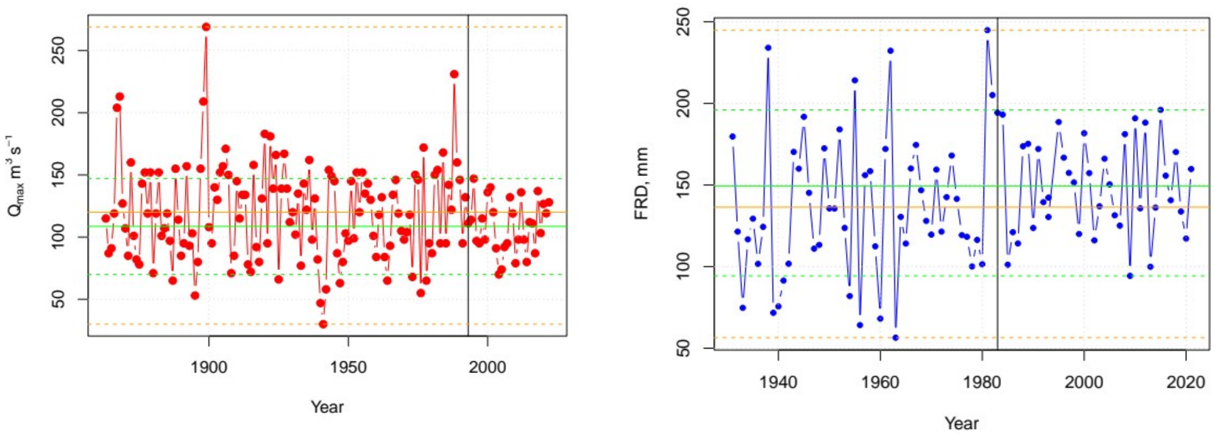


Figure 3. The percentage of the annual floods happening during the spring flooding period: 1930 – 2021 (gray), 1930 – 2000 (green) and 2001 – 2021 (right).

We applied the moving window technique to define the year when the step change (shift) happened in the multi-year records of the maximum water discharge (the annual flood in Table 3) and the volume of spring flood (the spring flood). The length of the moving window was equal to 15 and 30 years. The Student test (T-test) and Kolmogorov-Smirnov and Mann–Whitney statistical tests were applied (KS-test and U-test); to define the step change we used the 0.05 level of the statistical significance. Figure 4 a shows the time series of the annual floods in the Kokemaenjoki River: the step change was defined in 1993 (the vertical black line). The first period covers 1863–1993 when the average of yearly maximum water discharge equaling 120 m^3s^{-1} (orange solid line). The second period lasts from 1994 to 2021, the average of the yearly maximum water discharge is equal to 108 m^3s^{-1} (green solid line). The dotted lines indicate the range between minimum and maximum water discharges for two periods.



(a) (b)

Figure 4. The step change in the time series: (a) the annual floods in Kokemäenjoki River at Muroleenkoski site; (b) the volume of spring floods in Lieksanjoki River at Ruunaa site.

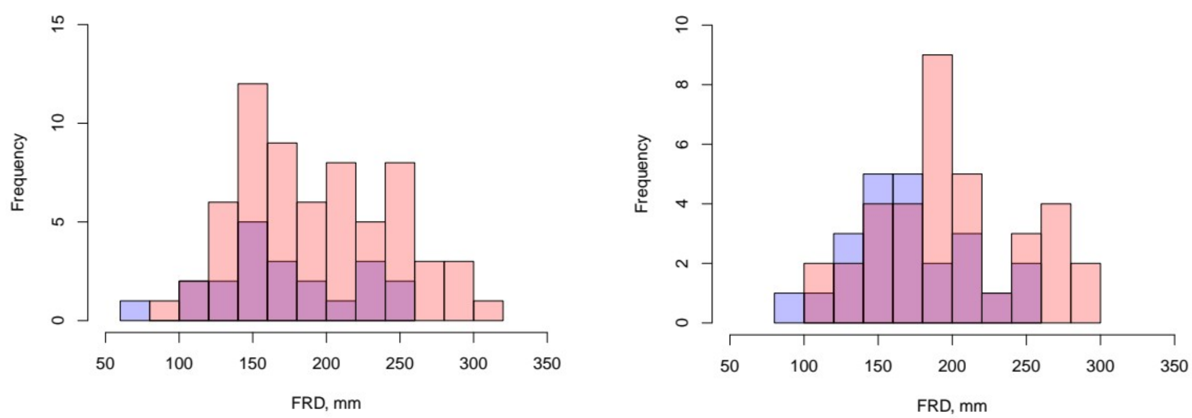
Our results show that the shifts were defined in 80 % of the records on the volume of spring floods (by the T-test); and in 50 % of the records on the annual floods (by the KS-test and/or U-test). Many of the shifts dated to late 1980s or early 1990s in 36 % of the records on the annual floods; the magnitude of the annual floods was both decreasing and increasing. Table 3 shows whether the step changes were defined in the records of the volume of spring floods and the annual floods.

Table 3. The step changes in the time series of the volume of spring flood and the annual floods. Notations: T-test is the Student's test, KS-test is the Kolmogorov-Smirnov's test and U-test is the Mann–Whitney test.

River	Spring floods			Annual floods		
	T-test	KS-test	U-test	T-test	KS-test	U-test
Juutuanjoki	–	–	–	–	–	–
Vantaanjoki	+/ 1992-2003	–	–	+/1968-1990, 2001, 2002	+/1970-1980, 1982, 1983, 1986, 1987	–
Tornionjoki	+/ 1940, 1948, 1949, 1991, 1992	–	–	+ / 1940, 1963-1967, 1991, 1992	+ / 1952, 1964-1967, 1971-1973	+ / 1992
Ouluujoki	– /	+ / 1957, 1964	– /	– /	– /	– /

Kokemäenjoki	+ /1993, 2003	– /	– /	+ /1991, 2003	+ / 1993	– /
Lieksanjoki	+ /1979, 1981	+ /1964, 1988	– /	– /	+/ 1981	– /
Tana	+/1951, 1952	– /	– /	– /	– /	– /
Ponoy	+ /1949, 1974	+ /1964, 1975	+ / 1975	– /	– /	– /
Pinega	+/1952, 1990	+ /1986, 1989	+ / 1989	+ / 1975, 2005	+ / 1982, 1989	+ / 1989
Pechora	+ / 1969	– /	– /	– /	– /	– /
Vim	– /	– /	– /	+ / 1951	– /	+ / 1951
Sula	+ / 1985	+ / 1985	– /	– /	– /	– /

Figure 5 shows histograms (an empirical probability in each range of a random value) which were calculated for two periods in the records of the volume of spring floods. In the Figure 5 a, the step change divides the records into two sub-series with the length of 80 and 31 years (before and and after the step change detected in 1991). For the first period, the mean, the coefficient of variation, the coefficient of skewness are estimated with the least uncertainties (Tables 5 and 6). The uncertainties inherent in estimation of the coefficient of skewness are large for the second period, and the asymmetry of the PDF may be accurate estimated from the ratio between the coefficients of variation and skewness (Rozhdestvenskiy and Chebotarev, 1974).



(a) (b)

Figure 5. Two histograms estimated from the sub-series of the volume of spring floods in Tornionjoki River at Ruunaa site (a) and in Ponoy River at Kanevka site (b).

The non-shited periods, their length estimated from the records on the volume of the spring floods and annual floods are given in Tables 4 and 5. These tables also showed the average (m), the coefficient of variation (CV) and the coefficient of skewness (CS) estimated for longest periods. The shifts (step-changes) are defined in the records on the volume of the spring floods that happened to 42 % river catchments. The volume of the spring floods decreases according to the records collected in Vantaanjoki River, which is the southernmost catchment selected within the study domain. The volume of spring floods increases according to the records collected in four rivers located in northern Finland and Russia (Table 4). The shifts dated to the late 1980s, since then the spring floods in the rivers increased in their volume by 11 – 38 %. The CV slightly decreases in most of the records while the CS increases.

Table 4. The average (*m*), the coefficient of variation (*CV*), the coefficient of skewness (*CS*), the auto-correlation (Pearson) coefficient for 1 year time lag (*r(1)*). The statistical estimators are estimated for from the time series of the spring flood runoff depth.

River	Period(s)	Length	m ± σ_m	CV ± σ_{CV}	CS ± σ_{CS}	CS/CV*
Juutuanjoki	1930 – 2012	84	150 ± 5	0.30 ± 0.04	0.59 ± 0.28	2.0
Vantaanjoki	1937 – 1993	57	95.8 ±5.2	0.41 ± 0.06	0.33 ± 0.35	1.0
	1994 – 2021	28	71.7 ± 5.2	0.38 ± 0.08	0.41 ± 0.50	
Tornionjoki	1911 – 1991	80	153 ± 5	0.29 ± 0.03	0.21 ± 0.28	1.0
	1992 – 2021	31	170 ± 6	0.21 ± 0.04	-0.25 ± 0.45	
Oulujoki	1911 – 2021	110	172 ± 4	0.24 ± 0.02	0.14 ± 0.24	1.5
Kokemäenjoki	1863 – 2021	160	111 ± 3	0.36 ± 0.03	0.49 ± 0.21	1.0
Lieksanjoki	1931 – 2021	91	142 ± 4	0.27 ± 0.03	0.20 ± 0.27	
Tana	1930 – 1952	23	170 ± 10	0.27 ± 0.06	0.07 ± 0.53	
	1953 – 2021	66	194 ± 6	0.26 ± 0.03	0.24 ± 0.31	1.0
Ponoy	1933 – 1975	43	160 ± 7	0.24 ±0 .04	0.01 ± 0.38	
	1976 – 2020	45	193 ± 7	0.23 ± 0.04	0.32 ± 0.37	1.5
Pinega	1936 – 1989	53	171 ± 6	0.26 ±0 .04	0.12 ± 0 .35	0.5
	1990 – 2020	30	236 ± 14	0.28 ± 0.05	[0.07] ± [0.47]	
Pechora	1936 – 2020	85	273 ± 7	0.21 ± 0.02	-0.05 ± 0.27	0.0
Vim	1937 – 2020	84	164 ± 5	0.26 ± 0.03	0.35 ± 0.27	1.5
Sula	1936 – 2020	84	214 ± 5	0.22 ± 0.02	0.34 ± 0.27	1.5

* the ratio is calculated for the longest period and it is rounded to the nearest value [0, 0.5, 1.0, 1.5 or 2.0].

Table 5. The average (*m*), the coefficient of variation (*CV*), the coefficient of skewness (*CS*). The statistical estimators are estimated for from the time series of the yearly maximum water discharge (Q_{max})

River	Period(s)	Length	$m \pm \sigma_m$	$CV \pm \sigma_{CV}$	$CS \pm \sigma_{CS}$	CS/CV*
Juutuanjoki	1930 – 2013	84	315 ± 13	0.37 ± 0.04	0.85 ± 0.29	2.0
Vantaanjoki	1937 – 1988	52	139 ± 6	0.33 ± 0.05	1.14 ± 0.36	3.5
	1989 – 2021	33	115 ± 5	0.26 ± 0.05	–0.09 ± 0.44	
Tornionjoki	1911 – 1992	81	2146 ± 54	0.23 ± 0.03	0.53 ± 0.28	2.5
	1993 – 2021	30	238 5 ± 84	0.19 ± 0.04	-0.14 ± 0.46	
Oulujoki	1911 – 2021	110	77.4 ± 2.2	0.30 ± 0.03	0.38 ± 0.24	1.0
Kokemäenjoki	1863 – 2021	160	118 ± 3	0.31 ± 0.03	0.67 ± 0.21	2.0
Lieksanjoki	1931 – 2021	91	146 ± 4	0.26 ± 0.03	0.24 ± 0.27	1.0
Tana	1930 – 2021	89	1569 ± 54	0.32 ± 0.04	0.59 ± 27	2.0
Ponoy	1933 – 2020	88	702 ± 17	0.21 ± 0.02	-0.32 ± 0.26	–1.5
Pinega	1936 – 1989	51	3565 ± 154	0.31 ± 0.05	0.71 ± 0.35	2.0
	1990 – 2020	30	[2588]± 274	[0.51] ± 0.10	[0.35] ± 0.50	
Pechora	1936 – 2020	85	1446 ± 40	0.24 ± 0.03	0.54 ± 27	2.0
Vim	1937 – 1951	15	1539 ± 140	0.35 ± 0.09	0.001 ± 0.67	
	1952 – 2020	69	2059 ± 88	0.33 ± 0.04	0.36 ± 0.31	1.0
Sula	1936 – 2020	84	1190 ± 33	0.24 ± 0.03	0.89 ± 0.27	4.0

* the ratio is calculated for the longest period and it is rounded to the nearest value [1.0, 1.5, 2.0, 3.5 or 4].

The shifts were found in the records on the annual floods that happened to four river catchments; and two of them are located in Finland. The annual floods increase in average according to the records of Tornionjoki River, and decrease according to the records collected in Vantaanjoki River (Table 5). The shifts dated to the late 1980s and early 1990s. In the shifts, the CV and CS were decreased; however, the length of the shortest records limits the accuracy of the CS.

5 Discussion

We studied the long term records on the annual floods and spring floods that happened in 12 rivers located in Finland and norther Russia. The rivers are unregulated and their catchments differ in physiography, however, they are located in the region with the cold climate (the subtype Dfc in the Köppen classification). The hydrological records on the daily water discharge were extracted from the yearly book published by the national hydrological agencies; the longest record covers the period 1863–2021. The previous studies focused on the hydrological regime of the rivers located in Finland and northern Russia rely on the observations ended by the mid 2000s (Veijalainen et al., 2010; Korhonen and Kuusisto, 2010; Shevnina et al., 2017).

The hydrological regime of 25 Finnish rivers has been studied by Kornonen and Kuusisto (2010) applying the records on monthly water discharges to evaluate the volume of river flow passing during the winter, spring, summer and autumn seasons dated to the calendar (where the spring season lasted from March to May). In Finland, the spring flooding period does not coincide with a calendar spring (Mustonen, 1986). Jónsdóttir et al., (2006) suggest to fix dates while defining the spring flooding period in the rivers located in Iceland (from April to June). In our study, we define the dates when a spring flood begins and ends from the hydrograph, and our results are difficult to compare with those mentioned above. Shevnina (2015) uses the daily hydrograph to define the length of spring flooding period in 34 rivers located in the Russian Arctic. The timing of the spring flooding period has been evaluated with the accuracy of 5-6 days in more than 80 % floods Shevnina (2013). In this study we applied the same method to evaluate when the spring flooding period begins and ends in the Finnish rivers.

Our results suggest that over 85 % of annual floods occur during the spring flooding period in the rivers located in northern Finland and the Russian Federation. The snow melt is the dominant source of the annual floods in Finland and northern Russia, and it agrees with previous studies (Mustonen, 1986; Korhonen and Kuusisto, 2010; Kaluzhny and Lavrov, 2012). However, in the last two decades, the number of annual floods sourced by snowmelt decreased almost twice in the rivers located in southern Finland where up to 43 % of the annual floods happen in the autumn-winter period. In the future, the warmer climate will expand towards northern Europe (Jylhä et al., 2010; Beck et al. 2018), and it affects the dominant source for the annual floods in Finland and northern Russia. It requires new methods to estimate the extreme floods sourced by rains and rains-on-snow.

The shifts or/and trends have been detected in historical records of river runoff (annual, seasonal) and river freeze-up and break-up dates, the shifts start in early 2000s (Hannaford and Marsh, 2008; Hirsch and Ryberg, 2011; Yip et al. 2012; Helama et al., 2013; Rosmann et al., 2016; Mangini et al., 2018; Blöschl et al., 2019; Kemter et al., 2020). The observations collected in many rivers located in Canada and the United State reveal the statistically significant trends in the records of the spring maximum flow which is decreasing in magnitude and in event timing (Burn et al., 2010; Bennett et al., 2015). Mediero et al. (2015) study dominant drivers, spatial and temporal patterns in the yearly highest floods that happen to 102 rivers located in Europe; the records collected in two Finnish rivers (Kokemaenjoki River and Tana River) are included. Authors analyze the trends in the records on the annual floods, but the analysis of the shifts has not been performed. No statistically significant trends or shifts have been found in the observations on the yearly maximum water discharge collected in 25 rivers located in Finland (Korhonen and Kuusisto, 2010). The statistically significant trends in the records on the maximum water discharge observed in the spring flooding period have been obtained in five rivers located in northern Finland (Irannezhad et al., 2022). We did not analyze the records on the maximum water discharge passing in the spring flooding period, and our results are difficult to compare.

The shifts (step changes) have been detected in the hydrological records on the volume of spring floods that happened in more than forty percent of the rivers located in northern Russia, and the year of the step changes dates to the early 1990s (Shevnina, 2011). The author uses the observations covering over 70 years (until 2007); and in this study we extended the records until 2020. Our results suggested the step changes (shifts) defined in the records on the annual floods and spring floods happening in almost half of the rivers. The shifts were found in the records on the volume of spring floods that happened to 42 % of the selected rivers; and the volume of spring floods increased in 33 % of the rivers located in northern Finland and Russia. The step changes in the records of the annual floods dated to the early 1950s, mid 1970s and early 1990s. The year of shifts dated to the late 1980s, since then the spring floods in the rivers increased in their volume by 11 – 38 %. The increase in the volume of spring floods may link to changes in winter precipitation, and in the future it would need to identify how coherent they are with the volume of floods happening in the river catchments located north of Finland and Russia.

Our results show that in the shifts on the annual floods recorded, the CV slightly decreases while the CS increases. In general, any change in CS highly affects the tailed probabilities (the extremes). The uncertainties inherent in the CS's estimate which we estimated from short records ($n < 60$ years) are huge; in this case, applying the CV/CS ratio is recommended (Rozhdestvenskiy, Chebotarev, 1978). The records show that the hydrological regime has already changed in many rivers within the domain under the study, and it would suggest revising the risks of the transport infrastructure which related to the floods in the rivers located northern Finland and the Russian Federation.

Two periods (before and after a shift) were defined in the records on the volume of spring flood, and this subdivision is needed in the parameterization and verification of the probabilistic hydrological models (Shevnina, 2015; Shevnina el al., 2017). The effectiveness of the earliest models is over 74 % while assessing the extreme floods that happened to the rivers located in the Russian Arctic (Shevnina et al., 2017). The results of this study allows us to set-up the latest version of the model (Shevnina and Silaev, 2019) for the geographic domain covering Finland and northern Russia. The next steps are (a) improving the model efficiency with new regional parameterization schemes, and (b) assessing the extreme floods based on results of climate models (and/or their ensembles). The climate projections now include the information on the snow water equivalent, which may serve as the forcing for the probabilistic hydrological models. The information on the snow water equivalent is available from in-situ snow courses and/or retreated from remote observations (Pulliainen, 2006; Haberkorn, 2019; Tsang et al., 2022; Eppler et al., 2022). It allows improving the efficiency of the probabilistic models applied in the assessment of the extreme floods in the snow dominated regions such as northern Finland and Russia.

6 Conclusions

The spring flooding period begins by the end of April and ends by June in most rivers located in Finland and northern Russia. The length of the spring flooding period varied between 43 and 97 days. The spring flooding period (> 80 days) is longer in the large rivers which are regulated by swamps and lakes, and it is shorter (< 50 days) in the rivers with small catchment areas. The contribution of the spring flood flow to the annual flow varied from 32 % to 53 % with increasing toward the north.

In the last two decades, the annual floods in the southernmost Finnish rivers often happened in the autumn-winter season during “rain-on-snow” events. In the future, the warmer climate will affect the dominant source for the highest floods, and it would need new estimates of the extreme floods sourced by heavy rain and rains-on-snow. The snow melt remains the dominant source for the annual floods happening to most rivers in northern Finland and Russia.

The shifts in the records on the annual floods and volume of spring floods were found according to the observations collected at 33–45 % of the rivers located in Finland and northern Russia. The shifts in the volume of spring floods dated to the early 1980s or 1990s; since then the spring floods in the rivers have increased in their volume by 21 % on average. The shifts in the hydrological records collected in many rivers located in northern Finland and the Russian Federation show that the coefficient variation and coefficient of skewness have also changed. This effect on the occurrence of the extreme floods; it suggests revising the risks of the transport infrastructure which are related to the river floods.

Annex

We calculated the mean (m), the coefficient of variation (*CV*), the coefficient of skewness (*CS*) and their errors with the formulas given in Rozhdestvenskiy and Chebotarev (1974):

$$m=\bar{x}=\frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

$$\sigma_m=\frac{\sigma_x}{\sqrt{n}} \qquad (2)$$

where, $\sigma_x=\sqrt{\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2}{n-1}}$.

$$CV=\sqrt{\frac{\sum_{i=1}^{n}\left(k_i-1\right)^2}{n-1}} \qquad (3)$$

where, $k_i=\frac{x_i}{\bar{x}}$.

$$\sigma_{CV}=\frac{CV}{\sqrt{2n}}\sqrt{1+CV^2} \qquad (4)$$

$$CS=\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^3}{n\sigma^3} \qquad (5)$$

$$\sigma_{CS}=\sqrt{\frac{6}{n}\left(1+CV^2\right)} \qquad (6)$$

In the equations, *x* is the hydrological value; *n* is the length of the time series.

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Open Research

The volume of spring flood (in mm of the depth of runoff), the dates of spring flood begin and end, the length of spring flooding period, the yearly maximum daily discharge and its date were estimated for each year from the daily series of water discharges observed at the hydrometric sites. To define the dates of spring flood begin and end we applied the semi-empirical method given in Shevnina (2013). The series of volume of spring flood (in mm of the depth of runoff), the dates of spring flood begin and end, the length of spring flooding period, the yearly maximum daily discharge and its date are given in the dataset supplementing this study. The calculations were performed in the R-project environment: the [Dataset] with the characteristics of annual and spring floods, the step-change analysis and statistics are deposited in the Zenodo (Shevnina, 2023). Software for this research is available in Shevnina (2019), [with the access restricted by June 2024]. Such software must be findable and accessible via https://zenodo.org/record/8333825).

The daily series of water river discharges at the sites located in Finland were extracted from (a) the Global runoff database https://portal.grdc.bafg.de/ (for the period from beginning of the observations to 2017); (b) the archive of the Finnish Environmental Institute https://www.vesi.fi/karttapalvelu/ (for the period 2018 – 2020). The daily series of water discharges at the sites located in the Russian Federation were extracted from (a) the yearly hydrological books published by the State Hydrological Institute (for the period from the beginning of observation to 2007) which are available via website https://gis.favr.ru/opendata; (b) the automated information system for state monitoring of water bodies https://gmvo.skniivh.ru/ (for the period 2008 – 2020) and these series are available from its website (an authentication required).

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The dominant source and volume of highest river floods have shifted in Finland and northern Russia

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Key Points:

- In Finland and northern Russia, over 32–53 % of annual river flow passes during the spring flooding period may last 43-97 days.
- In the past two decades, winter rains have become the dominant source for the annual floods in the rivers located in southern Finland.
- The shifts were detected in 45% of the records on the annual and/or spring floods that happened to rivers in Finland and northern Russia.

Keywords: climate, river floods, hydrological regime, shifts, extremes, cold regions

Abstract

We analyzed observations on floods in rivers located in Finland and northern Russia where hazardous floods often happen during a spring flooding period. We evaluated the length of spring flooding periods, the volume of spring floods, the yearly maximum water discharges (annual floods) and their dates from hydrographs. The hydrographs were evaluated using the daily water discharges given in yearly books published by the national hydrological services. The long term time series of annual and spring floods were used to define shifts (step changes) by applying the moving window technique. Three statistical criteria namely the Student test, the Kolmogorov-Smirnov test and the Mann-Whitney test were used. Our results suggest that the annual floods were recorded in the spring flooding period in more than 85 % of the rivers selected. In the last two decades, the number of annual floods that happened in autumn-winter season increased almost twice in the southern Finnish rivers. The melting snow remains the dominant source for the highest floods in the rivers located in northern Finland and Russia. The step changes were defined in half of the time series of the annual floods and spring floods. In over a one-third of the records of the spring floods, the step changes dated to the late 1990s, since then the volume of floods increased by 21 % on average. The step changes in the records of the annual floods dated to the early 1950s, mid 1970s and early 1990s.

Plain Language Summary

River floods are among well known hazards in Europe damaging social infrastructure including roads. In Finland and northern Russia, the highest floods in rivers have been observed during a spring flooding period, and snow melt is a dominant source of these floods. We further investigated whether dominant sources and magnitude of highest river floods have changed during an observational period? Our results show that in the last two decades, rains have become an essential source to form the highest floods that happen to rivers located south of Finland. In the northern Finland, the snow melt is the dominant source for the highest river floods. The snow-sourced floods have become larger in volume since the early 1990s in 36–45 % of rivers located in northern Finland and Russia. It may require a new evaluation of the flood-related risks for the road infrastructures in these regions.

1 Introduction

Floods are among well known hazards; the river floods are natural events that become “extreme” if only they are dangerous for a social infrastructure. The extreme floods (also known as design floods) are needed while building roads, bridges, pipelines, dams and houses. The engineering hydrology defines the extreme floods statistically as events that happen once a 10, 50, 100, … 1000 years. The extreme floods are estimated from observations at sites in rivers and with statistical methods (ie. frequency analysis) or from modeling (WMO-168, 2009; Benson, 1968). The extreme floods are evaluated from the hydrological records on yearly maximum flood (highest peak water discharge in a year or annual flood) assuming no change in climate and hydrological regime happen in the future (Ashkar et al., 1988). The fact of the change does not allow extrapolating the river flood-related risks for roads, bridges and dams to the future (Milly et al., 2008; Kundzewicz et al., 2008; Madsen et al., 2013).

The climate is defined by a set of statistical estimators (ie. mean, median, percentiles) calculated from observations of the meteorological variables lasting a n-years period (Monin, 1986). The length of the period is often 30 years and these (“climatological”) periods are suggested by the World Meteorological Organization (WMO). Then, the one-two statistical estimates (moments) are evaluated for the climatological periods (ie. 1961-1990, 1991-2020 or 1970-2000). These periods are not necessarily linked to the periods when no statistically significant trends or step-changes are found in the observed hydrological series.

To define the hydrological regime, up to four statistical estimators (moments) are evaluated from the hydrological records applying methods from the extreme value (frequency) analysis (Sokolovskiy, 1968; WMO-168, 2009). In the frequency analysis, the probability of floods that rarely happen or not recorded in a history of instrumental observations (the extreme or design floods) are evaluated from the exceedance probability distributions. The engineering hydrology accepts the various skewed distributions, and the Pearson’s distributions are among others (Bulletin-17B, 1982; SP33-101-2003, 2004); to their contractions, up to four moments are needed to be known whether from observations or models (Sokolovskiy, 1968). The length of the observational period is crucial for the accuracy of the highest moments; only few records allow evaluation of the third statistical moment with an acceptable accuracy (Rozhdestvenskiy and Chebotarev, 1974).

The extreme floods in rivers are evaluated from the records of a yearly maximum water discharge observed in rivers; it is also known as the annual flood (WMO-385, 2012). Henceforth, we used this term to mention the yearly maximum water discharge. The annual floods have originated from various sources (natural and man-made), and their dominant source depends on the climate, river catchment properties and artificial regulation (Whitfield, 2012). In southern European rivers, the heavy rains, rain-on-snow events and dam failures are typical sources for the annual floods (Hall et al.; 2014). In northern Europe, the annual floods are often sourced by the snow (or/and ice) melt (Snorrason et al., 2000; Kaluzhny and Lavrov, 2012; Hodgkins et al., 2017); and they happen in the spring flooding period which does not coincide with a calendar spring lasting from March to May (Jónsdóttir et al., 2006; Hyvärinen and Puupponen, 1986). The dominant source of the annual floods in rivers changes toward a time (Whitfield, 2012; Bennet et al., 2015).

In changing hydrological regimes, the design floods cannot be evaluated only from the historical records; and the extreme floods are predicted using hydrological models (Madsen et al., 2013; Cherry et al., 2017). The conceptual process-based hydrological models simulate the river water discharge series (daily or sub-daily) from meteorological variables (precipitation and air temperature) given in forecasts. The conceptual hydrological models are run on a catchment scale on semi-distributed and distributed types (Beven and Kirkby, 1979; Lohmann et al., 1993; Lindström et al. 2010; Arheimer and Lindström, 2015; Donnelly et al., 2016; Hamman et al., 2018). The parameters of these hydrological models are calibrated from the observations at hydrometric sites (Hundecha et al.; 2016). The calibration includes manual tuning, and it becomes burdensome to compute the parameters for the periods with different hydrological regimes in case of a large number of catchments (Hundecha et al., 2016 and 2020). The spatial resolutions of variables given in the meteorological forecasts, their uncertainties and methods applied to set numerous parameters affect the results of the distributed hydrological models. The series of the river water discharges simulated by the conceptual hydrological models are considered as “observed records” in estimations of the extreme river floods applying methods of the frequency analysis (Benson, 1968; Bowman and Shenton, 1993; WMO-168, 2009; England et al. 2019).

The advanced frequency analysis approach offers an alternative to the conceptual hydrological models in the estimation of the extreme (design) floods in changing hydrological regimes (Kovalenko, 1993). In the advanced frequency analysis, the statistical estimators are simulated from the information given in the climate projections (Kovalenko, 2014); the time series of the river water discharges are not simulated. The methods of the approach implemented in the probabilistic hydrological models which may have up to four parameters calibrated from hydrometric observations at sites (Shevnina et al., 2017). The model’s parametrization required the estimations of three-four initial statistical moments to be known from the historical records for the periods differing in the hydrological regime (Shevnina and Silaev, 2019). The periods are divided by a year when the shifts (step-changes) are detected in the hydrological records using various statistical tests (WMO-168, 2009; Hall et al., 2014).

We analyzed the long term time series of the annual floods and volume of spring floods observed at 12 rivers we selected in Finland and northern Russia. In this region, the annual floods often happen during a spring flooding period and sourced by snow melt. We estimated the length of the spring flooding period, volume of the spring floods and timing and magnitude of the annual floods from hydrograph. Then, we analyzed the long term time series of the river floods with the statistical methods to define the year when the hydrological regimes have changed (shifted). The records with the shifts are needed for the parametrization of the probabilistic hydrological models.

2 Study area

The study focuses on the territory of Finland and northern Russia where the cold climate with cold summer and without dry season is dominated (Fig. 1 a). The annual mean temperature varied between 1.0 and 5.5 °C in central and southern Finland, and slightly less than -2 °C in northern Finland. The annual precipitation varied between 500 and 700 mm in southern and central Finland; it is about 600 mm in northern Finland, where about a half of the precipitation is snow (Jylhä et al., 2010). In northern Russia, the annual precipitation varied between 400 and 700 mm, and up to a half of the precipitation fall in a cold season lasting from October to April (Peel et al., 2007). The annual floods are often formed during the spring season due to snow melting (Hyvärinen and Puupponen, 1986; Sokolovskiy, 1968). The selected river catchments are located in northern Europe where the cold climate (subtype Df, with summer without dry season) is dominated (Fig. 1b), and in the future the climate subtype will change over the region (Fig. 1 c), and it affects the dominant source, magnitude of the extreme floods and their occurrence.

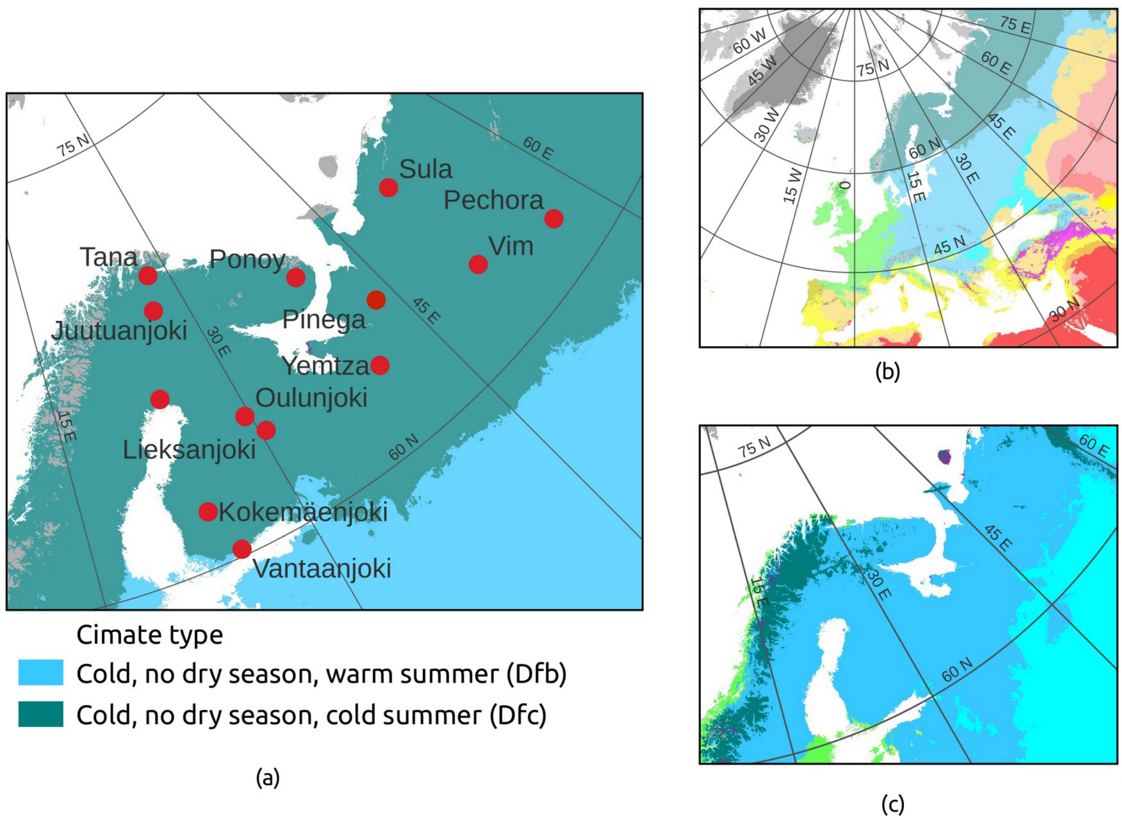


Figure 1. The location of the river catchments selected in this study: red dots indicate the location of the hydrometric sites; colors show the climate types / subtypes in the Köppen classification for the present (a, b) and the future (c) given according to Beck et al., (2018).

We selected 12 hydrometric sites that outlined the unregulated river catchments where the longest hydrometric records are published in the national hydrological books. The area of the river catchments varied from 1620 to 39000 km^2: two catchments with the area smaller than 5000 km^2, five catchments with the area between 5000 and 10000 km^2 and five catchments which are bigger than 10000 km^2. Most of the catchments are covered by the forest and tundra, or tundra mixed with swamp or wetland (Table 1).

Table 1. The location and physiography of river catchments selected in the study domain.

River – Gauge name	Lat	Observational	Catchment	Dominant land

		period / length	area, km^2	cover type(s)
Juutuanjoki – Savukkoniva	68.9	1930 – 2013 / 84	5160	Forest
Vantaanjoki – Oulunkylä	60.2	1937 – 2021 / 85	1620	Swamp
Tornionjoki – Karunki	66.0	1911 – 2021 / 111	39000	Forest
Oulujoki – Lentua, outlet	64.2	1911 – 2021 / 110	2045	Forest
Kokemäenjoki – Muroleenkoski	61.9	1863 – 2021 / 160	6102	Swamp, wetland
Lieksanjoki – Ruunaa	63.4	1931 – 2021 / 91	6260	Forest
Tana – Polmak Nye	70.1	1930 – 2018 / 89	14160	Tundra, swamp
Ponoy – Kanevka	67.1	1933 – 2020 / 88	10200	Tundra, swamp
Pinega – Kulogory	64.7	1936 – 2020 / 83	36700	Forest
Pechora – Yaksha	61.2	1936 – 2020 / 85	9620	Forest
Vim – Veslyana	63.0	1937 – 2020 / 84	19100	Forest
Sula – Kotkina	67.0	1936 – 2020 / 84	8500	Tundra

In Table 1, the area and dominant land cover types are given according to Gudmundsson et al., (2018) for the Finnish catchments, and according to the multi-year books (Yelshina and Kupriyanova, 1970; Vodogretskiy, 1972) for the catchments which are located in Russia. The numerous gaps dating to the early 1990s are in the records collected at the Russian sites.

3 Materials and Methods

The river runoff (annual, maximum, seasonal, monthly, etc) is estimated from water discharges measured at hydrometric sites. In this study, the river runoff was evaluated using (a) the daily water discharges given in the Global Runoff Data Center, GRDC dataset (https://www.bafg.de/ last access 12.01.2022); (b) the hydrological books published by the Finnish Environmental Institute (Finland) and the State Hydrological Institute (the Russian Federation); and (c) the information system for the monitoring of water bodies of the Russian Federation (https://gmvo.skniivh.ru/index.php?id=1, last access 10.10.2022).

The length of spring flooding period and volume of spring floods were evaluated from the hydrographs. The dates when the spring flooding event begins and ends were calculated as follows:

$$DYB = \left[D\left(t\right) \geq A\right] \wedge \left[T \geq B\right]$$

$$DYE = \left[D\left(t\right) < 0\right], \left[D\left(t+1\right) > 0\right] \wedge \left[Q \underset{\approx}{\rightarrow} CQ_m\right]$$

where $D(t) = Q(t-1) - Q(t)$ and $D(t+1) = Q(t-2) - Q(t)$; Q is the daily water discharge (m^3s^{-1}); T is length of the period when $D(t+1) - D(t) > 0$ (day); Q_m is the average daily water discharge in January and February; *A*, *B* and *C* are the empirical coefficients equaling 5.6, 5 and 3 as it is suggested for the river catchments located in northern Russia. These equations allow us to define the dates with the accuracy of 5-8 days; the errors inherent in the estimation of the volume of the spring flooding period do not exceed 10 % (Shevnina, 2013). The volume of flow passing the site during the spring flooding period was integrated over a period of spring flood event, and it divided to the river catchment area to express the volume in the depth of runoff (mm). We estimated how many flows pass in a spring flooding period compared to the flow passing in a year. We also estimated the date when the yearly maximum water discharge was recorded in each year, and then marked whether it happened during the spring flooding period or not.

We applied the hydrological records on the yearly maximum water discharge (annual flood) and volume of spring flood to define the periods differring in their hydrological regimes. The step changes (shifts) in the time series were evaluated with the moving window technique (Ducré-Robitaille et al., 2003; Kovalenko, 1993). In this technique, the whole period is divided into two periods: the length of the first period equals a chosen minimum, and the length of the second period equals a length of the whole period minus a chosen minimum). For two periods, the difference in the statistics is evaluated with statistical tests; then, the length of the first period is increased by 1; the calculations are repeated until the length of the second period becomes equal to the chosen minimum (Shevnina et al., 2017). With this technique, three statistical tests namely the Student test (the parametric test), the Kolmogorov-Smirnov test and the Mann-Whitney test (two non-parametric tests) were applied (Mitropolsky, 1961; Rozhdestvenskiy and Saharyuk, 1981). We used the 0.05 level of the statistical significance in defining the step changes in the time series (Rozhdestvenskiy and Chebotarev, 1974).

The probabilistic hydrological models ingest the precipitation and air temperature (averaged over n-year period) to be known from observations or climate projections (Shevnina and Silaev, 2019). The models' cross-validation procedure requires the statistical moments to be known from observed series of river runoff for two periods which were defined by the moving window technique. Then, the mean (m), the coefficient of variation (*CV*), the coefficient of skewness (*CS*) were calculated from the statistical moments (Rozdestvenskiy and Chebotarev, 1974). The uncertainties inherent in the statistical estimators were calculated with the formulas given in the Annex.

4 Results

The length of the spring flooding period and volume of spring flood were calculated from the dates when a flooding event begins (*DFB*) and ends (*DFE*) which were estimated from the daily water discharges (hydrograph). Figure 2 shows the hydrographs for two rivers where the annual floods happen during (a) a spring flooding period (as in most rivers in northern Finland and northern Russia) and (b) a winter period (as in many rivers in southern Finland). The yearly maximum water discharge (annual flood) and its date (*DFMax* in Fig. 2) were calculated, it allows us to divide the floods into two groups depending whether they happened during the spring flooding event or not.

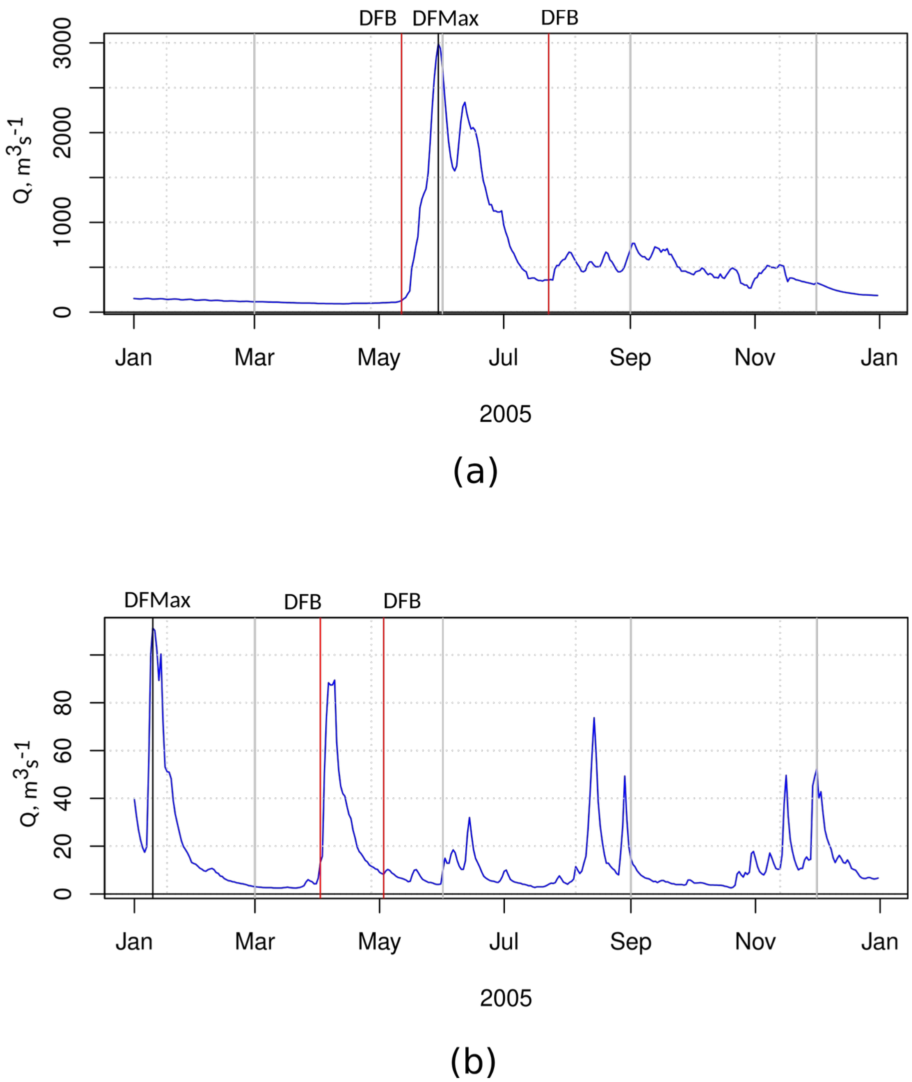


Figure 2. The dates of spring flood events begin and end (red lines) and date of the yearly maximum water discharge (black line) in Tornionjoki River at Karunki site (a) and in Vantaanjoki River at Oulunkylä site (b). The gray lines show the dates linked to the calendar seasons (winter, spring, summer and autumn).

In most rivers, the spring flooding period begins by the end of April, and it ends by June. The length of the spring flooding period varied between 43 and 97 days; the longer spring flooding period (>80 days) is estimated for the middle size river catchments located northern Finland; it is shorter than 60 days in the most northeastern Russian rivers. Table 2 shows the average for the length of the spring flooding period, the volume of the spring floods and the yearly maximum water discharges and their dates. The contribution of the spring flood flow to the annual flow varied from 32 % (Sula River) to 53 % (Pechora River); the contribution rises from the south to the north.

Table 2. The average of the volume of spring flood (*FRD*, mm), the average of the dates of spring flood begin and end (*DFB* and *DFE*), the average of the length of spring flooding period (*LFP*, day of year), the average of the maximum daily water discharge (Q_{max}, m^3s^{-1}) and its date (Df_{max}); N_s is a percent of the annual floods sourced by snow melt.

River	Spring flood			Annual flood		D_f	N_s
	DFB	*LFP*	*FRD*, mm m ± σ_m	Df_{max}	Q_{max}, m^3s^{-1} m ± σ_m		
Juutuanjoki	09.05	66	150 ± 5	26.05	315 ± 13	0.44	100
Vantaanjoki	29.03	43	87.9 ± 4	23.05	130 ± 5	0.36	72
Tornionjoki	29.04	75	158 ± 4	28.05	2210 ± 47	0.48	100
Oulunjoki	29.04	86	172 ± 4	29.05	77.4 ± 2.2	0.43	98
Kokemäenjoki	15.04	94	111 ± 3	04.06	118 ± 3	0.40	80
Lieksanjoki	24.04	97	142 ± 4	21.06	146 ± 4	0.37	85
Tana	05.03	61	188 ± 5	27.03	1569 ± 54	0.51	100
Ponoy	04.05	72	177 ± 5	24.05	702 ± 17	0.51	100
Pinega	28.04	54	191 ± 7	16.05	3269 ± 145	0.45	100
Pechora	28.04	56	273 ± 7	22.05	1446 ± 40	0.53	100
Vim	28.04	50	164 ± 5	16.06	1954 ± 79	0.46	86
Sula	06.05	56	214 ± 5	27.05	1190 ± 33	0.32	100

More than 85 % of the annual floods in the rivers were recorded during the spring flooding period. In two southernmost rivers, 20-28 % of the annual floods are recorded in the late autumn or winter periods. Figure 3 shows the number of annual floods that happened during the spring flooding period in five rivers in three different periods. We estimated this number from the hydrological records for (a) the whole observational period, (b) the period from early 1930s to 2000; and (c) the period from 2001 to 2021. In the southernmost Vantaanjoki River, the number of annual floods sourced from snow melt has decreased almost twice in the last two decades (left plot in Fig. 3); it can be said that rain has contributed essentially to form the highest floods in rivers located southern Finland. Since the 2000s, only 43 % of the annual floods were recorded during the spring flooding period in Vantaanjoki River. In the northern rivers (Oulunjoki River, Vim River), the snow melt still remains the dominant source for the annual floods.

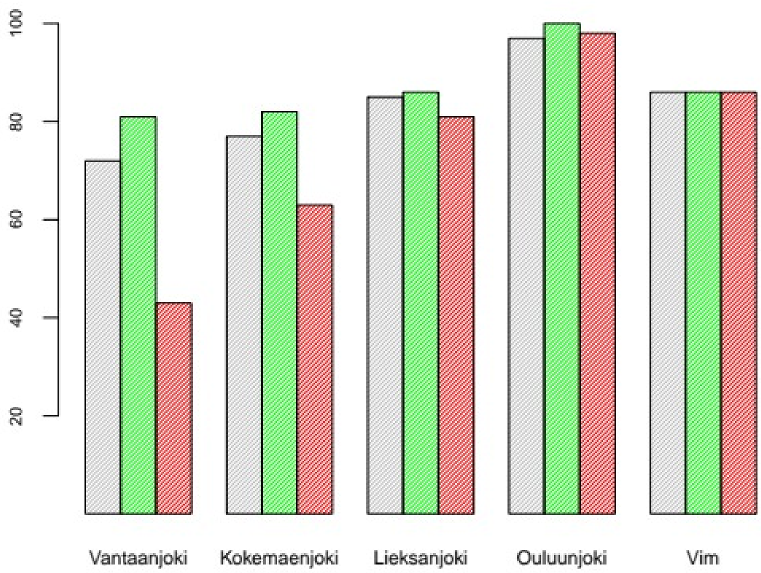
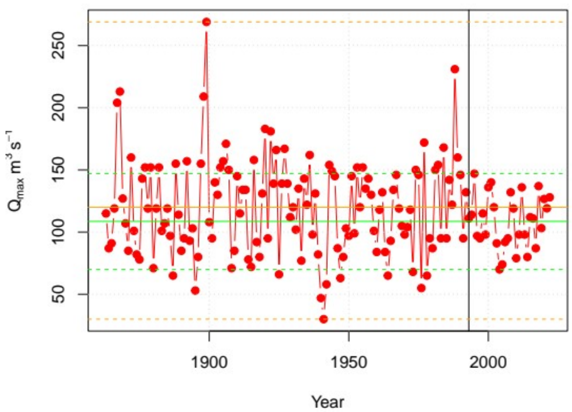
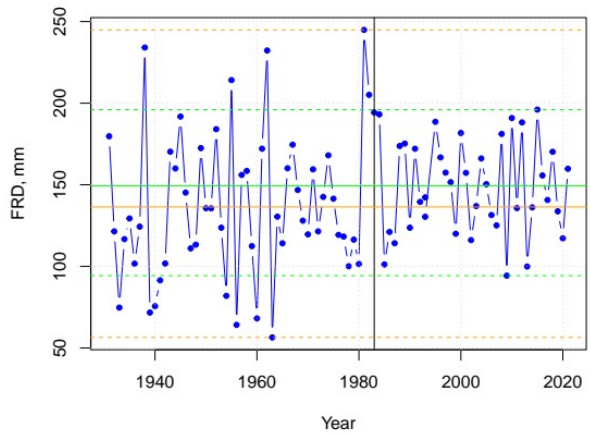


Figure 3. The percentage of the annual floods happening during the spring flooding period: 1930 – 2021 (gray), 1930 – 2000 (green) and 2001 – 2021 (right).

We applied the moving window technique to define the year when the step change (shift) happened in the multi-year records of the maximum water discharge (the annual flood in Table 3) and the volume of spring flood (the spring flood). The length of the moving window was equal to 15 and 30 years. The Student test (T-test) and Kolmogorov-Smirnov and Mann–Whitney statistical tests were applied (KS-test and U-test); to define the step change we used the 0.05 level of the statistical significance. Figure 4 a shows the time series of the annual floods in the Kokemaenjoki River: the step change was defined in 1993 (the vertical black line). The first period covers 1863–1993 when the average of yearly maximum water discharge equaling 120 m^3s^{-1} (orange solid line). The second period lasts from 1994 to 2021, the average of the yearly maximum water discharge is equal to 108 m^3s^{-1} (green solid line). The dotted lines indicate the range between minimum and maximum water discharges for two periods.



(a)



(b)

Figure 4. The step change in the time series: (a) the annual floods in Kokemäenjoki River at Muroleenkoski site; (b) the volume of spring floods in Lieksanjoki River at Ruunaa site.

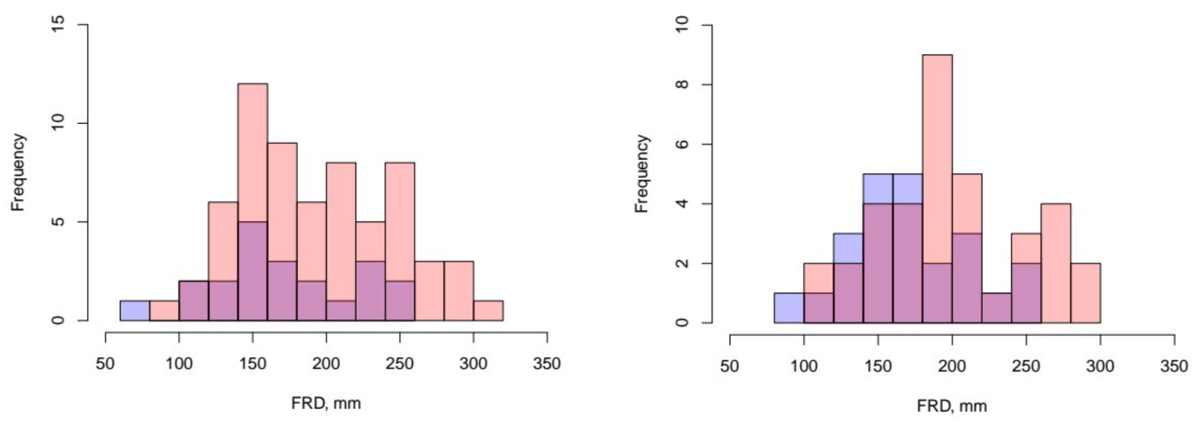
Our results show that the shifts were defined in 80 % of the records on the volume of spring floods (by the T-test); and in 50 % of the records on the annual floods (by the KS-test and/or U-test). Many of the shifts dated to late 1980s or early 1990s in 36 % of the records on the annual floods; the magnitude of the annual floods was both decreasing and increasing. Table 3 shows whether the step changes were defined in the records of the volume of spring floods and the annual floods.

Table 3. The step changes in the time series of the volume of spring flood and the annual floods. Notations: T-test is the Student's test, KS-test is the Kolmogorov-Smirnov's test and U-test is the Mann–Whitney test.

River	Spring floods			Annual floods		
	T-test	KS-test	U-test	T-test	KS-test	U-test
Juutuanjoki	–	–	–	–	–	–
Vantaanjoki	+/ 1992-2003	–	–	+/1968-1990, 2001, 2002	+/1970-1980, 1982, 1983, 1986, 1987	–
Tornionjoki	+/ 1940, 1948, 1949, 1991, 1992	–	–	+ / 1940, 1963-1967, 1991, 1992	+ / 1952, 1964-1967, 1971-1973	+ / 1992
Ouluujoki	– /	+ / 1957, 1964	– /	– /	– /	– /

Kokemäenjoki	+ /1993, 2003	– /	– /	+ /1991, 2003	+ / 1993	– /
Lieksanjoki	+ /1979, 1981	+ /1964, 1988	– /	– /	+/ 1981	– /
Tana	+/1951, 1952	– /	– /	– /	– /	– /
Ponoy	+ /1949, 1974	+ /1964, 1975	+ / 1975	– /	– /	– /
Pinega	+/1952, 1990	+ /1986, 1989	+ / 1989	+ / 1975, 2005	+ / 1982, 1989	+ / 1989
Pechora	+ / 1969	– /	– /	– /	– /	– /
Vim	– /	– /	– /	+ / 1951	– /	+ / 1951
Sula	+ / 1985	+ / 1985	– /	– /	– /	– /

Figure 5 shows histograms (an empirical probability in each range of a random value) which were calculated for two periods in the records of the volume of spring floods. In the Figure 5 a, the step change divides the records into two sub-series with the length of 80 and 31 years (before and and after the step change detected in 1991). For the first period, the mean, the coefficient of variation, the coefficient of skewness are estimated with the least uncertainties (Tables 5 and 6). The uncertainties inherent in estimation of the coefficient of skewness are large for the second period, and the asymmetry of the PDF may be accurate estimated from the ratio between the coefficients of variation and skewness (Rozhdestvenskiy and Chebotarev, 1974).



(a) (b)

Figure 5. Two histograms estimated from the sub-series of the volume of spring floods in Tornionjoki River at Ruunaa site (a) and in Ponoy River at Kanevka site (b).

The non-shited periods, their length estimated from the records on the volume of the spring floods and annual floods are given in Tables 4 and 5. These tables also showed the average (m), the coefficient of variation (CV) and the coefficient of skewness (CS) estimated for longest periods. The shifts (step-changes) are defined in the records on the volume of the spring floods that happened to 42 % river catchments. The volume of the spring floods decreases according to the records collected in Vantaanjoki River, which is the southernmost catchment selected within the study domain. The volume of spring floods increases according to the records collected in four rivers located in northern Finland and Russia (Table 4). The shifts dated to the late 1980s, since then the spring floods in the rivers increased in their volume by 11 – 38 %. The CV slightly decreases in most of the records while the CS increases.

Table 4. The average (*m*), the coefficient of variation (*CV*), the coefficient of skewness (*CS*), the auto-correlation (Pearson) coefficient for 1 year time lag (*r(1)*). The statistical estimators are estimated for from the time series of the spring flood runoff depth.

River	Period(s)	Length	m ± σ_m	CV ± σ_{CV}	CS ± σ_{CS}	CS/CV*
Juutuanjoki	1930 – 2012	84	150 ± 5	0.30 ± 0.04	0.59 ± 0.28	2.0
Vantaanjoki	1937 – 1993	57	95.8 ±5.2	0.41 ± 0.06	0.33 ± 0.35	1.0
	1994 – 2021	28	71.7 ± 5.2	0.38 ± 0.08	0.41 ± 0.50	
Tornionjoki	1911 – 1991	80	153 ± 5	0.29 ± 0.03	0.21 ± 0.28	1.0
	1992 – 2021	31	170 ± 6	0.21 ± 0.04	-0.25 ± 0.45	
Oulujoki	1911 – 2021	110	172 ± 4	0.24 ± 0.02	0.14 ± 0.24	1.5
Kokemäenjoki	1863 – 2021	160	111 ± 3	0.36 ± 0.03	0.49 ± 0.21	1.0
Lieksanjoki	1931 – 2021	91	142 ± 4	0.27 ± 0.03	0.20 ± 0.27	
Tana	1930 – 1952	23	170 ± 10	0.27 ± 0.06	0.07 ± 0.53	
	1953 – 2021	66	194 ± 6	0.26 ± 0.03	0.24 ± 0.31	1.0
Ponoy	1933 – 1975	43	160 ± 7	0.24 ±0 .04	0.01 ± 0.38	
	1976 – 2020	45	193 ± 7	0.23 ± 0.04	0.32 ± 0.37	1.5
Pinega	1936 – 1989	53	171 ± 6	0.26 ±0 .04	0.12 ± 0 .35	0.5
	1990 – 2020	30	236 ± 14	0.28 ± 0.05	[0.07] ± [0.47]	
Pechora	1936 – 2020	85	273 ± 7	0.21 ± 0.02	-0.05 ± 0.27	0.0
Vim	1937 – 2020	84	164 ± 5	0.26 ± 0.03	0.35 ± 0.27	1.5
Sula	1936 – 2020	84	214 ± 5	0.22 ± 0.02	0.34 ± 0.27	1.5

* the ratio is calculated for the longest period and it is rounded to the nearest value [0, 0.5, 1.0, 1.5 or 2.0].

Table 5. The average (*m*), the coefficient of variation (*CV*), the coefficient of skewness (*CS*). The statistical estimators are estimated for from the time series of the yearly maximum water discharge (Q_{max})

River	Period(s)	Length	$m \pm \sigma_m$	$CV \pm \sigma_{CV}$	$CS \pm \sigma_{CS}$	CS/CV*
Juutuanjoki	1930 – 2013	84	315 ± 13	0.37 ± 0.04	0.85 ± 0.29	2.0
Vantaanjoki	1937 – 1988	52	139 ± 6	0.33 ± 0.05	1.14 ± 0.36	3.5
	1989 – 2021	33	115 ± 5	0.26 ± 0.05	–0.09 ± 0.44	
Tornionjoki	1911 – 1992	81	2146 ± 54	0.23 ± 0.03	0.53 ± 0.28	2.5
	1993 – 2021	30	238 5 ± 84	0.19 ± 0.04	-0.14 ± 0.46	
Oulujoki	1911 – 2021	110	77.4 ± 2.2	0.30 ± 0.03	0.38 ± 0.24	1.0
Kokemäenjoki	1863 – 2021	160	118 ± 3	0.31 ± 0.03	0.67 ± 0.21	2.0
Lieksanjoki	1931 – 2021	91	146 ± 4	0.26 ± 0.03	0.24 ± 0.27	1.0
Tana	1930 – 2021	89	1569 ± 54	0.32 ± 0.04	0.59 ± 27	2.0
Ponoy	1933 – 2020	88	702 ± 17	0.21 ± 0.02	-0.32 ± 0.26	–1.5
Pinega	1936 – 1989	51	3565 ± 154	0.31 ± 0.05	0.71 ± 0.35	2.0
	1990 – 2020	30	[2588]± 274	[0.51] ± 0.10	[0.35] ± 0.50	
Pechora	1936 – 2020	85	1446 ± 40	0.24 ± 0.03	0.54 ± 27	2.0
Vim	1937 – 1951	15	1539 ± 140	0.35 ± 0.09	0.001 ± 0.67	
	1952 – 2020	69	2059 ± 88	0.33 ± 0.04	0.36 ± 0.31	1.0
Sula	1936 – 2020	84	1190 ± 33	0.24 ± 0.03	0.89 ± 0.27	4.0

* the ratio is calculated for the longest period and it is rounded to the nearest value [1.0, 1.5, 2.0, 3.5 or 4].

The shifts were found in the records on the annual floods that happened to four river catchments; and two of them are located in Finland. The annual floods increase in average according to the records of Tornionjoki River, and decrease according to the records collected in Vantaanjoki River (Table 5). The shifts dated to the late 1980s and early 1990s. In the shifts, the CV and CS were decreased; however, the length of the shortest records limits the accuracy of the CS.

5 Discussion

We studied the long term records on the annual floods and spring floods that happened in 12 rivers located in Finland and norther Russia. The rivers are unregulated and their catchments differ in physiography, however, they are located in the region with the cold climate (the subtype Dfc in the Köppen classification). The hydrological records on the daily water discharge were extracted from the yearly book published by the national hydrological agencies; the longest record covers the period 1863–2021. The previous studies focused on the hydrological regime of the rivers located in Finland and northern Russia rely on the observations ended by the mid 2000s (Veijalainen et al., 2010; Korhonen and Kuusisto, 2010; Shevnina et al., 2017).

The hydrological regime of 25 Finnish rivers has been studied by Kornonen and Kuusisto (2010) applying the records on monthly water discharges to evaluate the volume of river flow passing during the winter, spring, summer and autumn seasons dated to the calendar (where the spring season lasted from March to May). In Finland, the spring flooding period does not coincide with a calendar spring (Mustonen, 1986). Jónsdóttir et al., (2006) suggest to fix dates while defining the spring flooding period in the rivers located in Iceland (from April to June). In our study, we define the dates when a spring flood begins and ends from the hydrograph, and our results are difficult to compare with those mentioned above. Shevnina (2015) uses the daily hydrograph to define the length of spring flooding period in 34 rivers located in the Russian Arctic. The timing of the spring flooding period has been evaluated with the accuracy of 5-6 days in more than 80 % floods Shevnina (2013). In this study we applied the same method to evaluate when the spring flooding period begins and ends in the Finnish rivers.

Our results suggest that over 85 % of annual floods occur during the spring flooding period in the rivers located in northern Finland and the Russian Federation. The snow melt is the dominant source of the annual floods in Finland and northern Russia, and it agrees with previous studies (Mustonen, 1986; Korhonen and Kuusisto, 2010; Kaluzhny and Lavrov, 2012). However, in the last two decades, the number of annual floods sourced by snowmelt decreased almost twice in the rivers located in southern Finland where up to 43 % of the annual floods happen in the autumn-winter period. In the future, the warmer climate will expand towards northern Europe (Jylhä et al., 2010; Beck et al. 2018), and it affects the dominant source for the annual floods in Finland and northern Russia. It requires new methods to estimate the extreme floods sourced by rains and rains-on-snow.

The shifts or/and trends have been detected in historical records of river runoff (annual, seasonal) and river freeze-up and break-up dates, the shifts start in early 2000s (Hannaford and Marsh, 2008; Hirsch and Ryberg, 2011; Yip et al. 2012; Helama et al., 2013; Rosmann et al., 2016; Mangini et al., 2018; Blöschl et al., 2019; Kemter et al., 2020). The observations collected in many rivers located in Canada and the United State reveal the statistically significant trends in the records of the spring maximum flow which is decreasing in magnitude and in event timing (Burn et al., 2010; Bennett et al., 2015). Mediero et al. (2015) study dominant drivers, spatial and temporal patterns in the yearly highest floods that happen to 102 rivers located in Europe; the records collected in two Finnish rivers (Kokemaenjoki River and Tana River) are included. Authors analyze the trends in the records on the annual floods, but the analysis of the shifts has not been performed. No statistically significant trends or shifts have been found in the observations on the yearly maximum water discharge collected in 25 rivers located in Finland (Korhonen and Kuusisto, 2010). The statistically significant trends in the records on the maximum water discharge observed in the spring flooding period have been obtained in five rivers located in northern Finland (Irannezhad et al., 2022). We did not analyze the records on the maximum water discharge passing in the spring flooding period, and our results are difficult to compare.

The shifts (step changes) have been detected in the hydrological records on the volume of spring floods that happened in more than forty percent of the rivers located in northern Russia, and the year of the step changes dates to the early 1990s (Shevnina, 2011). The author uses the observations covering over 70 years (until 2007); and in this study we extended the records until 2020. Our results suggested the step changes (shifts) defined in the records on the annual floods and spring floods happening in almost half of the rivers. The shifts were found in the records on the volume of spring floods that happened to 42 % of the selected rivers; and the volume of spring floods increased in 33 % of the rivers located in northern Finland and Russia. The step changes in the records of the annual floods dated to the early 1950s, mid 1970s and early 1990s. The year of shifts dated to the late 1980s, since then the spring floods in the rivers increased in their volume by 11 – 38 %. The increase in the volume of spring floods may link to changes in winter precipitation, and in the future it would need to identify how coherent they are with the volume of floods happening in the river catchments located north of Finland and Russia.

Our results show that in the shifts on the annual floods recorded, the CV slightly decreases while the CS increases. In general, any change in CS highly affects the tailed probabilities (the extremes). The uncertainties inherent in the CS's estimate which we estimated from short records ($n < 60$ years) are huge; in this case, applying the CV/CS ratio is recommended (Rozhdestvenskiy, Chebotarev, 1978). The records show that the hydrological regime has already changed in many rivers within the domain under the study, and it would suggest revising the risks of the transport infrastructure which related to the floods in the rivers located northern Finland and the Russian Federation.

Two periods (before and after a shift) were defined in the records on the volume of spring flood, and this subdivision is needed in the parameterization and verification of the probabilistic hydrological models (Shevnina, 2015; Shevnina el al., 2017). The effectiveness of the earliest models is over 74 % while assessing the extreme floods that happened to the rivers located in the Russian Arctic (Shevnina et al., 2017). The results of this study allows us to set-up the latest version of the model (Shevnina and Silaev, 2019) for the geographic domain covering Finland and northern Russia. The next steps are (a) improving the model efficiency with new regional parameterization schemes, and (b) assessing the extreme floods based on results of climate models (and/or their ensembles). The climate projections now include the information on the snow water equivalent, which may serve as the forcing for the probabilistic hydrological models. The information on the snow water equivalent is available from in-situ snow courses and/or retreated from remote observations (Pulliainen, 2006; Haberkorn, 2019; Tsang et al., 2022; Eppler et al., 2022). It allows improving the efficiency of the probabilistic models applied in the assessment of the extreme floods in the snow dominated regions such as northern Finland and Russia.

6 Conclusions

The spring flooding period begins by the end of April and ends by June in most rivers located in Finland and northern Russia. The length of the spring flooding period varied between 43 and 97 days. The spring flooding period (> 80 days) is longer in the large rivers which are regulated by swamps and lakes, and it is shorter (< 50 days) in the rivers with small catchment areas. The contribution of the spring flood flow to the annual flow varied from 32 % to 53 % with increasing toward the north.

In the last two decades, the annual floods in the southernmost Finnish rivers often happened in the autumn-winter season during “rain-on-snow” events. In the future, the warmer climate will affect the dominant source for the highest floods, and it would need new estimates of the extreme floods sourced by heavy rain and rains-on-snow. The snow melt remains the dominant source for the annual floods happening to most rivers in northern Finland and Russia.

The shifts in the records on the annual floods and volume of spring floods were found according to the observations collected at 33–45 % of the rivers located in Finland and northern Russia. The shifts in the volume of spring floods dated to the early 1980s or 1990s; since then the spring floods in the rivers have increased in their volume by 21 % on average. The shifts in the hydrological records collected in many rivers located in northern Finland and the Russian Federation show that the coefficient variation and coefficient of skewness have also changed. This effect on the occurrence of the extreme floods; it suggests revising the risks of the transport infrastructure which are related to the river floods.

Annex

We calculated the mean (m), the coefficient of variation (*CV*), the coefficient of skewness (*CS*) and their errors with the formulas given in Rozhdestvenskiy and Chebotarev (1974):

$$m=\bar{x}=\frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

$$\sigma_m=\frac{\sigma_x}{\sqrt{n}} \tag{2}$$

where, $\sigma_x=\sqrt{\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2}{n-1}}$.

$$CV=\sqrt{\frac{\sum_{i=1}^{n}\left(k_i-1\right)^2}{n-1}} \tag{3}$$

where, $k_i=\frac{x_i}{\bar{x}}$.

$$\sigma_{CV}=\frac{CV}{\sqrt{2n}}\sqrt{1+CV^2} \tag{4}$$

$$CS=\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^3}{n\sigma^3} \tag{5}$$

$$\sigma_{CS}=\sqrt{\frac{6}{n}\left(1+CV^2\right)} \tag{6}$$

In the equations, x is the hydrological value; n is the length of the time series.

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Open Research

The volume of spring flood (in mm of the depth of runoff), the dates of spring flood begin and end, the length of spring flooding period, the yearly maximum daily discharge and its date were estimated for each year from the daily series of water discharges observed at the hydrometric sites. To define the dates of spring flood begin and end we applied the semi-empirical method given in Shevnina (2013). The series of volume of spring flood (in mm of the depth of runoff), the dates of spring flood begin and end, the length of spring flooding period, the yearly maximum daily discharge and its date are given in the dataset supplementing this study. The calculations were performed in the R-project environment: the [Dataset] with the characteristics of annual and spring floods, the step-change analysis and statistics are deposited in the Zenodo (Shevnina, 2023). Software for this research is available in Shevnina (2019), [with the access restricted by June 2024]. Such software must be findable and accessible via https://zenodo.org/record/8333825).

The daily series of water river discharges at the sites located in Finland were extracted from (a) the Global runoff database https://portal.grdc.bafg.de/ (for the period from beginning of the observations to 2017); (b) the archive of the Finnish Environmental Institute https://www.vesi.fi/karttapalvelu/ (for the period 2018 – 2020). The daily series of water discharges at the sites located in the Russian Federation were extracted from (a) the yearly hydrological books published by the State Hydrological Institute (for the period from the beginning of observation to 2007) which are available via website https://gis.favr.ru/opendata; (b) the automated information system for state monitoring of water bodies https://gmvo.skniivh.ru/ (for the period 2008 – 2020) and these series are available from its website (an authentication required).

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[Water Resources Research]

Supporting Information for

[The dominant source and volume of highest river floods have shifted in Finland and northern Russia]

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The supporting information includes the dataset of the annual flood's characteristics (the maximum water discharge and its date and source) and the spring flood's characteristics (the dates when it begins and ends, the length of the spring flooding period, the volume of water passing in this period). The characteristics were calculated from the daily time series of water discharges observed at the hydrometric sites; the data were extracted from the hydrological books published by the national hydrological services of Finland and the Russian Federation. The date and magnitude of annual floods were previously estimated by Gudmundsson et al. (2018), and our estimates show a good agreement for these data for overlapping periods. The Pearson correlation coefficients were estimated to be 0.95-0.99 for the majority of the rivers.

The dataset consists of the CSV/TXT files, each file contains the long term series of the characteristics listed in the header: "year", "DFB" (date when a spring flooding period begins, day of year, DOY),"DFE" (date when the spring flooding period ends, DOY),"Length" (length of the spring flooding period, days), "DFMax" (date when the yearly maximum water discharge is recorded, DOY), "Qmax" (the yearly maximum water discharge, m^3s^{-1}), "FRD" (the volume of spring flood expressed in mm per flooding period), "YRD" (volume of annual flow, expressed in mm per year),"Ftype" (the source of annual flood equaling to 1 of the yearly maximum water discharge is recorded in the spring flooding period or 0 if it is not). Table S1 shows a list with the name of rivers (hydrometric sites) together with the name of the files in the dataset. The files are compressed in the file named as Supplement_Shevnina2023 which is attached to the manuscript. It is also available by a request via elena.shevnina@fmi.fi.

Table S1. The list of the files in the dataset supplemented to the manuscript.

River – Gauge name	River – Gauging sites
JuutuanjokiSP.txt	Juutuanjoki – Savukkoniva

Vantaanjoki_sp.csv	Vantaanjoki – Oulunkylä
Torniojoki_sp.csv	Tornionjoki – Karunki
OulunjokiSP.txt	Oulujoki – Lentua, outlet
KokemaenjokiSP.txt	Kokemäenjoki – Muroleenkoski
LieksanjokiSP.txt	Lieksanjoki – Ruunaa
TanaSP.txt	Tana – Polmak Nye
Ponoy_sp.csv	Ponoy – Kanevka
Pinega_sp.csv	Pinega – Kulogory
Pechora_sp.csv	Pechora – Yaksha
VimSP.txt	Vim – Veslyana
Sula_sp.csv	Sula – Kotkina