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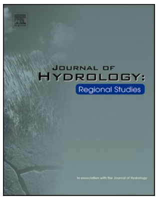

Changes in the discharge regime of Finnish rivers

Karoliina Lintunen[a,*], Elina Kasvi[a], Cintia B. Uvo[b,c], Petteri Alho[a,d]

[a] *Department of Geography and Geology, University of Turku, Turku FI-20014, Finland*
[b] *Finnish Environment Institute SYKE, Marine and Freshwater Solutions, Latokartanonkaari 11, Helsinki FI-00790, Finland*
[c] *Department of Water Resources Engineering, Lund University, Box 118, Lund, SE 22100, Sweden*
[d] *Finnish Geospatial Research Institute FGI, National Land Survey of Finland, Vuorimiehentie 5, FI-02150 Espoo, Finland*

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ABSTRACT

Study region: Finland divided into three subregions, each representing different environmental conditions.
Study focus: This study investigates long-term changes in unregulated river discharge. Trends in high- and low-flow event volumes, magnitudes, timings, and frequencies are analysed across 36 gauging stations in 19 watershed areas from 1911 to 2021. The average measurement period for discharge in the stations is 60 years, with over 765,000 daily records examined statistically.
New hydrological insights for the region: High-flow events show advancing timings and decreasing magnitudes, notably in the coastal region and less so in the north. These events, occurring from 6 to 68 days earlier in 21 stations, now in the late winter and early spring, align with increasing spring low-flow volumes. On a monthly scale, a trend of rising volume magnitude is observed in late autumn, winter, and early spring, especially in Northern Finland's rivers. High flows during autumn and winter occur 30 to 60 days later in 8 stations. Changes in the monthly mean volumes were found in 30 stations, suggesting a redistribution of annual volumes across a broader time period, while the overall annual volumes have remained relatively unchanged. This underscores the complexity of hydrological patterns, emphasizing the need to consider total volumes and their temporal distribution in analyses. The findings enhance understanding of current changes and align with findings in the boreal-subarctic area.

1. Introduction

Global warming has caused rapid and remarkable changes in the Earth's climate since the 1950s, due to the substantial increase in greenhouse gas emissions, especially in high-latitude polar regions where more rapid warming is experienced than in any other region (IPCC, 2023).

Over the past decades, the Arctic regions have undergone a warming trend exceeding the global average, with the region continuing to warm at a rate more than twice as fast as the rest of the world (Druckenmiller et al., 2022). This has led to noticeable warming in cold regions and wetting in Northern Europe (Gudmundsson et al., 2017). Furthermore, climate change has been observed to intensify the water cycle and lead to alterations in the flow regime (Blöschl et al., 2017). In northern regions, where the annual floods are typically caused by spring snowmelt and rain, the effects of climate change on runoff and flooding are anticipated to be more pronounced compared to other regions (Barnett et al., 2005). Consequently, it is crucial to measure changes in natural flow patterns to

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* Corresponding author.
E-mail address: emklin@utu.fi (K. Lintunen).

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fully understand the impact of these changes. To comprehensively understand the past and future effects of climate change and climate variability, long-term dataset analyses are essential. Such analyses hold great significance for modelling future climate scenarios, validating them, and effectively managing water resources. Changes in river discharges are essential factors for assessing the effects of climate change on the hydrological cycle as discharges are highly dependent on precipitation, evapotranspiration, and changes in water storage across the entire watershed area (White et al., 2007). To achieve this objective, flow values provide the most comprehensive insights due to their extensive network of measurement stations and extended temporal coverage (Hannah et al., 2011).

Recent years have seen extensive research into the impacts of climate change on flow patterns in global (Fang et al., 2022; Gudmundsson et al., 2019; Blöschl et al., 2017; White et al., 2007), regional (Burn and Whitfield, 2017; Matti et al., 2017; Hall et al., 2014; Wilson et al., 2010), and national (Venegas-Cordero et al., 2022; Stevens et al., 2016; Vormoor et al., 2016; Ilnicki et al., 2014; Apsīte et al., 2013; Klavins and Rodinov, 2008) scales. Various studies have linked the changes in flow patterns in cold regions to alterations in precipitation and temperature due to global warming, and severe changes in the hydrological cycle have been predicted (Stadnyk et al., 2021; Gelfan et al., 2017; Barnett et al., 2005). Hence, national-scale discharge regime studies are needed to assess the effects of global warming and to provide current research outcomes for national policymakers and researchers. Some studies have been conducted on the long-term changes in the Finnish river discharge regime in both regulated and unregulated rivers (Gohari et al., 2022; Korhonen and Kuusisto, 2010; Hyvärinen, 2003). However, there is need to consider how climate change has affected to the discharges recently and during the measurement history to provide information for future decision-making and research. This is especially crucial in the Arctic and subarctic regions, where changes are occurring rapidly.

In Arctic and subarctic regions, studies of flow patterns have been conducted with increasing interest in recent decades. In their analysis of discharges in Canada and the United States, Burn and Whitfield (2017) observed an upward trend in flood magnitudes and changes in the mean flood dates during the period from 1915 to 2014. Notably, a significant finding was the increase in the occurrence of flood events outside the snowmelt season. This aligns with an earlier study by Burn et al. (2010) focusing on hydrological extremes in Canadian watersheds. The 2010 study identified a decrease in annual and snowmelt-induced spring maximum flows occurring earlier, coupled with an increase in the frequency of flood events associated with rainfall. Wilson et al. (2010) studied trends in Nordic streamflow and concluded that, since 1920, streamflow patterns in the Nordic countries have undergone alterations, although the specific trends may vary depending on the analysed time frame. Later, Vormoor et al. (2016) studied flooding in Norway and found that rainfall has progressively become a more significant factor in generating floods, whereas the influence of snowmelt has diminished, and that snowmelt-dominated floods are occurring earlier. Similarly, in Sweden, Arheimer and Lindström (2015) identified certain indications of a seasonal shift in flooding trends. Although no significant long-term trends were found, the study revealed diminishing spring flood magnitudes and an increase in autumn flood magnitudes over the past century.

Already decades ago, patterns indicating heightened winter flows in Southern, Western, and Central Finland as a result of warmer winters were identified (Hyvärinen, 1998, 2003; Hyvärinen and Leppäjärvi, 1989; Hyvärinen and Vehviläinen, 1981). Korhonen and Kuusisto (2010) conducted the latest study on the Finnish river discharge regime focusing on long-term changes in flow volumes and timings in 25 Finnish rivers, spanning from the mid-1800s to 2004. Their results indicated changes in the seasonal distribution of streamflow with increases in mean monthly discharges during winter and spring. However, they did not detect changes in the magnitudes of spring high flows or autumn flows. Their study also included regulated watersheds, where interpreting changes in terms of climate change is more complex due to the indirect reflection of temporal hydrological changes. Blöschl et al. (2019) focused their study on Europe, including Finland. They noted that flood discharges in Finland decreased from 1960 to 2010 with some exceptions in Lapland. Together with decreases in flooding, decreases in maximum monthly soil moisture were also found, whereas the maximum 7-day precipitation and mean spring temperature had increased at the rate of 0.5 °C per decade. Gohari et al. (2022) investigated variations in extreme flows within 16 rivers across Finland, comprising gauging station records from headwaters of regulated and unregulated watersheds, over the period from 1911 to 2020. They learned that during the last six decades, various trends in flow regimes have started and become more severe in the period of 1991 to 2020. Over the last century, rivers in Southern Finland have experienced more pronounced fluctuations in extreme flow events, including a new low-flow pattern during summer and a new high-flow pattern marked by frequent double peak flows before/after spring. The authors proposed climate change as the cause of the changes, but no further analysis of the reasons behind these trends has been conducted.

During this century, Finland's climate zones are expected to shift towards a prevailing type that is more temperate and characterized by increased precipitation (Jylhä et al., 2010). Based on the climate scenarios, Ruosteenoja and Jylhä (2021) projected that summer precipitation is projected to increase by 5% (90% uncertainty interval: -6 to 17%), and winter precipitation by 12% (0 to 24%) by the period of 2040–2069. Similarly, increases in the mean temperatures are projected to be 2.4 °C (1.0 to 3.8) during summer and 3.3 °C (1.2 to 5.4) in the winter. Projections also indicate an increase in the frequency of extreme precipitation events. By the end of the 21st century in Northern Europe, the 1-day maximum precipitation is expected to increase by 20% in winter and 10% in summer. Concurrently, consecutive dry-day periods are projected to decrease by 10% during winter and increase by 20% in summer (Lehtonen et al., 2014). Veijalainen et al. (2010). studied climate change impacts on flooding in Finland, revealing a significant shift in runoff and flood seasonality. Increased flooding during autumn and winter, along with decreased flooding in spring, was noted. In snowmelt-dominated regions, discharge is predicted to decrease by the end of this century under different climate scenarios. Areas prone to autumn and winter flooding were projected to experience increases, with notable changes observed, particularly in Southern and Central Finland. The magnitude of these changes was expected to peak by the end of the century, although shifts were already evident in the 2010–2039 projections.

This study examines long-term changes (over 25 years) in river discharge in unregulated rivers across Finland, involving 36 gauging stations from 19 watersheds. Unlike previous studies, we focus solely on unregulated rivers, providing a comprehensive analysis of both high and low-discharge events, along with their annual timing shifts. In total, 750,000 daily discharge measurements were analysed from 1911 to 2021, with the mean measurement period of gauging stations being 60 years. Analysis of long-term changes in discharge provides valuable knowledge for river management and therefore has a socioeconomic impact. This study examines recent discharge measurements and potential trends that have not been extensively studied before. A comparison of two different climatological normal periods is conducted to investigate more recent changes and to address how climate change has affected the discharge regime of unregulated rivers in Finland. Long-term changes are examined over entire observation periods and two climatological normal periods (1961–1990 and 1991–2020) according to the World Meteorological Organization's (WMO's) and the Finnish Meteorological Institute's (FMI's) definitions (Jokinen et al., 2021), in order to gain insights into broader trends and patterns. To achieve these goals, the study is divided into three main components: (1) investigating changes in discharge volumes and magnitudes; (2) exploring changes in high- and low-discharge event timings and frequencies; (3) and assessing the impact of climatic variables. The results of this study contribute to the understanding of the substantial changes in the hydrological cycle occurring in boreal-subarctic regions.

2. Study area

Finland is located within the boreal and temperate climate zone, and based on the Köppen-Geiger climate classification, most of the country experiences cold and short summers (Dfc), whereas the coastal regions have warmer summers (Dfb) (Peel et al., 2007) (Fig. 1). Precipitation in Finland varies by region, with the south and east having the highest levels and north receiving the least. Typical annual precipitation is approximately 600 millimetres (Irannezhad et al., 2014), and during the reference period of 1991–2020, annual

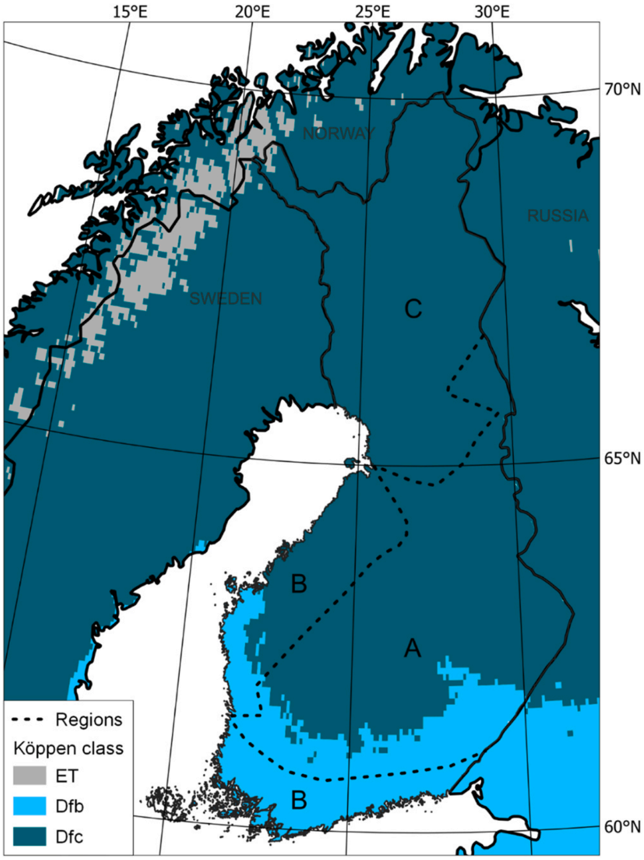

Fig. 1. Köppen climate classification of Finland (Rubel et al., 2017). Letters A, B, and C correspond to distinct regions within the Finnish river systems adapted from Korhonen and Kuusisto (2010). Köppen classes: ET = Arctic tundra climate; Dfb = cold humid warm summers; Dfc = cold humid cold summers.

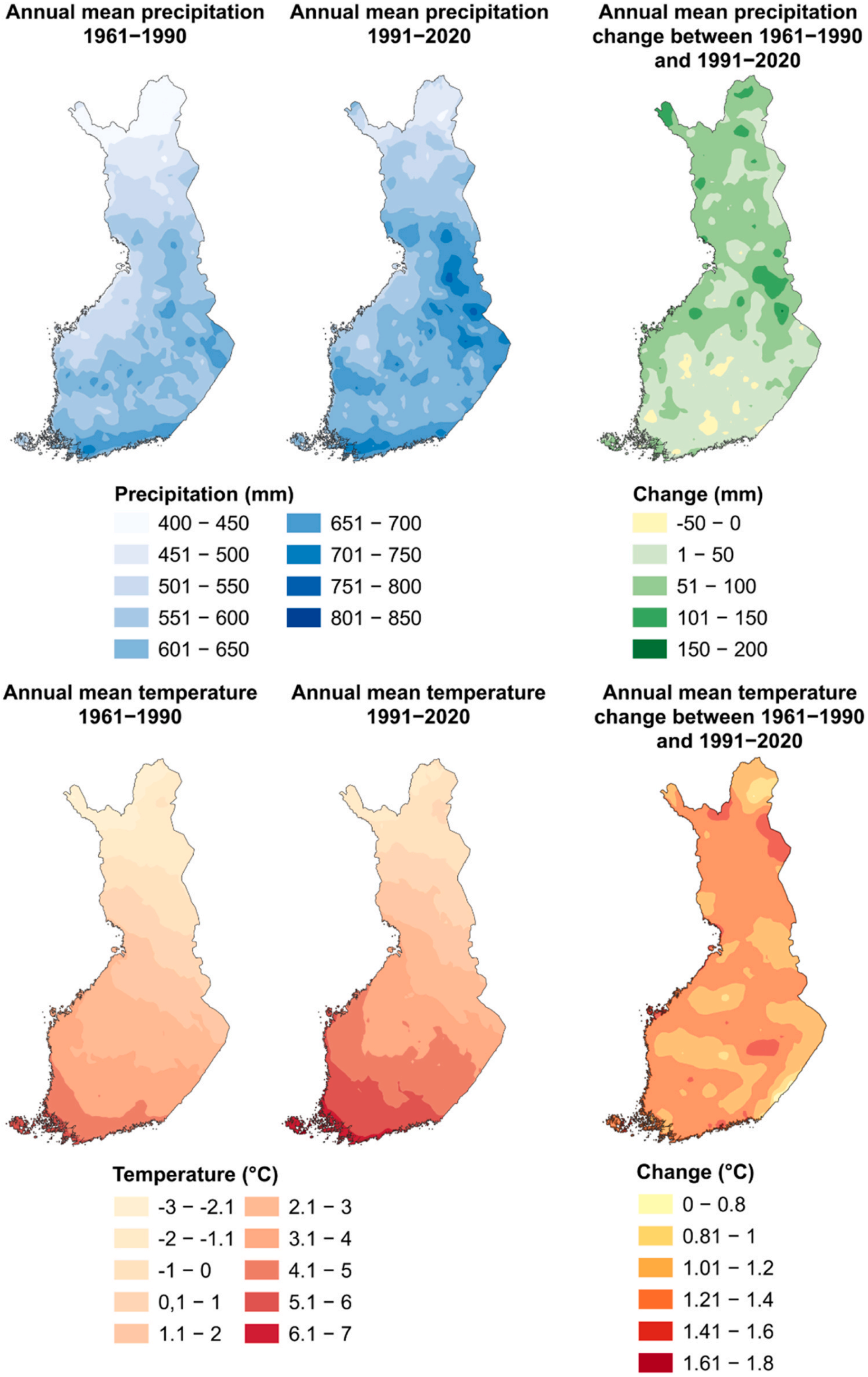

Fig. 2. Annual mean precipitation and temperature in Finland during climatological reference periods with the calculated changes in the variables between these periods (Finnish Meteorological Institute, 2023a, 2023b). The most pronounced shifts in annual mean precipitation are observed in Northern and Eastern Finland, while the temperature regions have shifted northward with a mean increase of 1°C.

precipitation varied between 450 and 700 millimetres (Jokinen et al., 2021). From 1961–1990 to 1991–2020, Jokinen et al., 2021 observed a 9% increase in precipitation, with the greatest growth occurring in December, January, and February and a decrease in August. Northern and Eastern Finland experience the highest increases, whereas certain areas in Southern Finland see slight decreases in mean annual precipitation between the two reference periods (Fig. 2). During the reference period of 1991–2020, the annual mean temperature varied between +5 and −2 °C. In comparison to 1961–1990, the newer reference period is about 1.3 °C warmer with the greatest change in December and the smallest in June and October. In the southern and central regions, persistent snow cover duration on the southern and western coasts decreased by over a month between 1961–1990 and 1991–2020, along with a significant reduction in the length of the thermal winter. Irannezhad et al. (2014) conducted an extensive evaluation of precipitation patterns in Finland from 1911 to 2011, discovering a statistically significant annual increase of 0.92 ± 0.50 mm/year ($p < 0.05$). In 1964, Finland shifted from a dry to a wet climate, marking a significant change in the precipitation regime, and the results suggest increased rainfall in recent decades compared to historical patterns.

The discharge regimes of Finnish rivers are characterized by precipitation patterns and the seasonal cycle (Olsson et al., 2015; Hyvärinen, 1986). In winter, river discharge decreases as temperatures drops and snow accumulates, leading to ice coverage. While rivers usually freeze annually, recent years have witnessed open-channel periods lasting through winter (Norrgård and Helama, 2019). The wintertime is succeeded by spring snowmelt, causing a peak in runoff and discharges. The highest discharges typically occur during this time, even though heavy precipitation during other periods might increase flows. As summer arrives, runoff and river discharges decrease, largely because of increased evaporation and the growing season. Following the end of the growing season in autumn, runoff and river discharges increase. Approximately half of the precipitation goes into runoff, whereas the other half is either stored or undergoes evapotranspiration. The mean annual runoff in Finland was 301 mm from 1931 to 1990 (Kuusisto, 1992), while during the period of 2000–2019, it increased to 320 mm (Tilastokeskus, 2020).

In this study, to ensure comparability with previous research, we use three region groups of river systems covering the whole Finland, initially defined by Hyvärinen (1986), and later used also by Korhonen and Kuusisto (2010) (Fig. 1). The division is based on the hydrological and environmental characteristics of the regions. The first group (region A) includes rivers and watersheds located in the Finnish lake region in Southern and Central Finland. In region A, watersheds typically have a substantial area of lakes, which allows for significant water storage, thereby mitigating seasonal discharge fluctuations. The second group (region B) comprises rivers from the coastal region that flow into the Gulf of Bothnia and the Gulf of Finland. In contrast to region A, region B features smaller watershed areas with fewer lakes, resulting in high and short-lived discharge peaks as well as periods of low flow. Finally, the third group (region C) encompasses rivers in Northern Ostrobothnia and Lapland. In region C, watershed areas are generally extensive, and the most significant discharge peaks typically occur in spring due to snowmelt.

3. Data

For this study, 36 gauging stations from 19 unregulated watershed areas with long-term hydrological records were selected (Fig. 3, Table 1). The highest annual mean discharge was at Pello (356.9 m^3/s) and lowest at Peerajärvi (1.6 m^3/s) gauging sites, both located in the Torne watershed. Sites were distributed around Finland to represent the catchment areas that vary in size and environmental characteristics (Fig. 3.). Most of the studied rivers flow to the Baltic Sea; however, some of them in Northern Finland flow to the Arctic Ocean. Lake Finland (region A) is underrepresented in the dataset; the area has many lakes instead of rivers, and a significant portion of watersheds are regulated. Daily hydrological datasets were acquired from the Finnish Environment Institute (SYKE) through their open information portal, and the length of the datasets varied between 28 and 110 years.

Discharge records of the hydrological sites are derived from the rating curve method, where discharge is determined based on the daily water level data. The records consisted of daily mean discharge values, from which statistics were calculated. From most of the main Finnish rivers, observations start from 1911, but many of them were regulated between 1945 and 1970 when most of the regulation schemes were created for flood prevention, hydropower, water transportation, and water supply (Korhonen and Kuusisto, 2010). During this same period, numerous observation series have gaps in their records due to interruptions in measurements and site relocations. In this study, the majority of the sites had daily gaps in their records, so for analysis, only months and years with over 90% of the data were included when necessary. As Korhonen and Kuusisto (2010) noted in their study, the trend analysis is highly dependent on the period chosen under analysis. Therefore, all the data in this study were analysed from the start year of the records until the year 2021 to acquire the longest possible period available. Analyses of the hydrological records were also conducted for 30-year periods following the WMO's and FMI's climatological normal periods (1961–1990 and 1991–2020) for comparison of possible changes and trends of hydrological data. Even though some of the hydrological records lacked a few years of a complete 30-year period (records from 1962: Alaköngäs, Hosionkoski, Inarijoki, Porkkalansilta, 1993: Kruunupyy, Lutto), they were still taken under analysis to gain a better and wider insight into variability between different climatological normal periods.

In some river sites ice cover, frazil ice, and ice damming can cause disturbance to the winter discharge measurements (Hyvärinen, 2003). In southern rivers, the ice reduction is quite low, and therefore the winter discharges have been rather accurate. In this approach, researchers tried to avoid problems related to ice by using verified discharge measurements and data from ice-free lake outlet measurements. However, it is possible that certain problems related to ice, such as the presence of ice cover disrupting the stage-discharge relationship at the gauging station, could still be within the datasets. It is important to note that although certain watershed areas may contain regulated water bodies, these do not influence the gauging sites under investigation as they are above the regulation influence area.

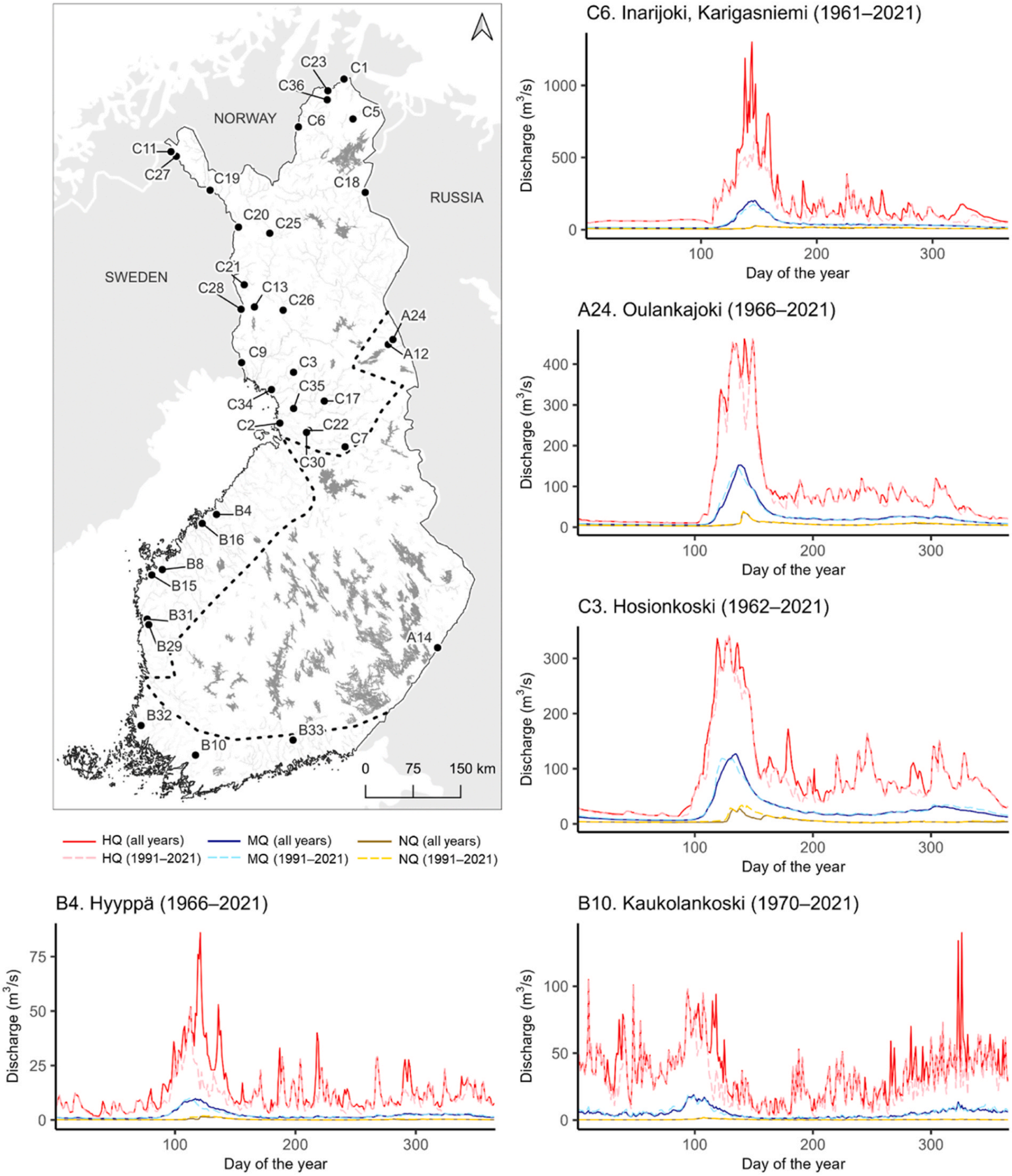

Fig. 3. Locations of the observation sites together with examples representing typical discharge regimes of the different regions. High discharge (HQ), mean discharge (MQ), and low discharge (NQ) are plotted for the whole observation period and the 1991–2020 period to represent different regions' discharge characteristics for the whole observation period and the 1991–2020 period. Letters A, B, and C on observation site names correspond to the discharge regions explained in the text. Grey areas inside the study area indicate waterbodies, i.e., lakes and rivers.

Table 1

Observation sites and their hydrological characteristics, including watershed area, region, observation period, lake percentage of the drainage area above the site (L%), mean annual discharge (m^3/s), and missing daily discharge values (%). More than 5 years of consecutive missing data gaps in the data are marked with *. Letters A, B, and C on observation site names correspond to the regions.

Observation site	Watershed area	Records since	Watershed A (km^2)	L (%)	Mean annual Q (m^3/s)	Missing daily Q values (%)
C1. Alaköngäs	Tana (Tenojoki)	1962	14002	3	178.8	0.0
C2. Haukipudas	Kiiminkijoki	1937	3814	3	44.6	0.0
C3. Hosionkoski	Simojoki	1962	1981	8.5	25.8	0.1
B4. Hyyppä	Kälviänjoki	1966	267	0.5	2.1	3.1
C5. Iijärvi (lake outlet)	Näätämöjoki	1951*	744	14.7	8.6	10.2
C6. Inarijoki, Karigasniemi	Tana (Tenojoki)	1961	3133	0.9	36.6	0.1
C7. Iso Puutiojärvi (lake outlet)	Kiiminkijoki	1975	371	4.6	4.5	0.1
B8. Karkkimala	Laihianjoki	1972	426	0	3.3	0.4
C9. Karunki	Torne (Tornionjoki)	1911	39385	5.4	392.6	0.0
B10. Kaukolankoski	Uskelanjoki	1970	481	0.7	4.9	2.1
C11. Kilpisjärvi (lake outlet)	Torne (Tornionjoki)	1952	293	14.7	4.9	1.1
A12. Kitkajoki, Käylä	Koutajoki	1971	1706	22.2	19.6	0.5
C13. Konttajärvi (lake outlet)	Torne (Tornionjoki)	1985	339	3.8	3.9	1.2
A14. Kontturi	Tohmajoki	1978	381	8.3	3.7	0.0
B15. Köpingsbro	Maalahdenjoki	1972	489	0.1	4.3	0.5
B16. Kruunupyy	Kruunupyynjoki	1993	768	2.8	6.9	5.7
C17. Livojoki, Hankikoski	Iijoki	1974	1981	3.1	26.9	0.0
C18. Lutto	Tulomajoki	1993	1628	2.2	21.2	3.8
C19. Muonionjoki, Kaaresuvanto	Torne (Tornionjoki)	1972	5732	3.4	86	0.2
C20. Muonionjoki, Muonio	Torne (Tornionjoki)	1959	9259	3.5	129.2	0.0
C21. Naamijoki	Torne (Tornionjoki)	1971	732	2.8	8	0.0
C22. Nuorittajoki	Kiiminkijoki	1967	1045	2.2	13	0.0
C23. Onnelansuvanto	Tana (Tenojoki)	1959	10864	2.1	140	0.0
A24. Oulankajoki	Koutajoki	1966	1986	4.8	24.5	0.1
C25. Ounasjoki, Köngäs	Ounasjoki	1941	4488	4.2	51	0.2
C26. Ounasjoki, Marraskoski	Ounasjoki	1919	12303	2.6	133.2	0.5
C27. Peerajärvi (lake outlet)	Torne (Tornionjoki)	1959	108	6.9	1.6	2.4
C28. Pello	Torne (Tornionjoki)	1959	33596	4.5	356.9	0.0
B29. Perus	Lapväärtinjoki	1970	976	0.2	13.2	0.0
C30. Porkkalan silta	Kiiminkijoki	1962	1855	3.8	22.5	0.0
B31. Puskamarkki	Teuvanjoki	1985	480	0.1	5.2	1.8
B32. Puttakoski	Sirppujoki	1970	340	0.8	3.4	1.1
B33. Pyhäjärvi (lake outlet)	Koskenkylänjoki	1954	460	6	4.3	0.1
C34. Simo	Simojoki	1911*	3109	5.8	44.9	8.1
C35. Siuruanjoki, Leuvankoski	Iijoki	1959	2379	1.8	31.5	1.2
C36. Utsjoki, Patoniva	Tana (Tenojoki)	1962	1520	2.6	17.9	1.5

4. Methods

Flow volumes and timings were analysed for total volumes, mean discharge (MQ), highest discharge (HQ), and lowest discharge (NQ) over different time frames, and a trend analysis was applied (Table 2). Analyses were conducted for the entire observation period of each site, as well as for the two 30-year climatological periods (1961–1990 and 1991–2020) defined by WMO and FMI for sites, which had records available. High- and low-flow magnitudes and timings were calculated annually for the whole calendar year, spring (Jan–Jun), and autumn (Jul–Dec) for 1, 3, 7, and 30 consecutive days. Analyses were applied to a calendar year to gain the possibility to compare results with the previous studies, and because this study did not account for wintertime, the hydrological year was not considered. The occurrence frequencies of flow events were determined on an annual basis, considering the same day periods (7 and 30 days) as those used for identifying high-flow timings. The observation period specific to each site served as the reference for these calculations. Subsequently, the obtained results were ranked. The timings of low-flow events were not analysed, as they can occur either during the dry summer season or in winter low-flow situations. Occurrences of flow frequencies were grouped over 10-year periods to detect decadal and regional differences. Calculations were conducted with R using the *fasstr* package, which compiles various functions to organize and filter daily flow data together with the possibility to conduct diverse analyses (Goetz and Schwarz, 2023).

Trend analyses were conducted using the Mann–Kendall trend test following other flow studies (Blöschl et al., 2017, 2019; Mangini et al., 2018; Korhonen and Kuusisto, 2010). The Mann-Kendall test is a non-parametric statistical test widely used to identify

Table 2
List of indexes used for the analyses of volume, magnitude, timing, and frequency. Analyses for detecting trends were conducted either using Mann–Kendall and Sen's Slope or annual frequency calculation. Each analysis was calculated for the whole observation period, 1961–1990 and 1991–2020 season, but frequencies were only calculated for the whole observation period.

Index	Abbreviation	Time scale
	Volume	
Total volume (m^3)	Total Q	Annual, seasonal (Jan–Jun or Jul–Dec), monthly
Low discharge (m^3/s)	NQ	Annual, seasonal (Jan–Jun or Jul–Dec), monthly
Mean discharge (m^3/s)	MQ	Annual, seasonal (Jan–Jun or Jul–Dec), monthly
High discharge (m^3/s)	HQ	Annual, seasonal (Jan–Jun or Jul–Dec), monthly
	Magnitude	
1, 3, 7, or 30-day low discharge (m^3/s)	1/3/7/30-day LQ	Annual, seasonal (Jan–Jun or Jul–Dec)
1, 3, 7, or 30-day high discharge (m^3/s)	1/3/7/30-day HQ	Annual, seasonal (Jan–Jun or Jul–Dec)
	Timing	
1, 3, 7, or 30-day high discharge (day of the year)	1/3/7/30-day HQ DoY	Annual, seasonal (Jan–Jun or Jul–Dec)
	Frequency	
7/30-day low discharge return period (years)	7/30-day LQ freq.	Annual
7/30-day high discharge return period (years)	7/30-day HQ freq.	Annual

monotonic trends in time series datasets (Kendall, 1975; Mann, 1945). The null hypothesis of the Mann-Kendall test states there is no significant trend in the dataset, whereas the alternative hypothesis states there is a significant trend present in the dataset. Trends were assessed for their significance with p-values considered significant at a 5% (0.05) significance level. Given that Mann-Kendall test results can be influenced by autocorrelation and that positive autocorrelation might cause the trend test to reject the null hypothesis (Hamed, 2009; Yue et al., 2002), the Zhang method to trend analysis, which removes lag-1 autocorrelation, was applied (Wang and Swail, 2001; Zhang et al., 2000). This procedure was built into the R package *fasstr* (Goetz and Schwarz, 2023) from the R package *zyp* (Bronaugh et al., 2023). In the Zhang approach (for full details, see Zhang et al., 2000) the series undergoes trend removal if the trend is statistically significant and the autocorrelation is calculated. The procedure persists until the differences in the estimates of the slope and the autoregressive order 1 (AR(1)) between two successive iterations are less than 1 percent. Afterwards, the significance was tested with a non-parametric Mann-Kendall trend test to assess whether there is a monotonic trend in the resulted discharge time series. The trend magnitude and direction (change per unit, in this study year) were calculated using the Theil-Sen approach (Sen's slope) (Sen, 1968; Theil, 1950), if a significant ($p < 0.05$) trend was detected. The Theil-Sen approach is a robust indicator widely used in hydrological research for trend magnitude assessment (Masseroni et al., 2021; Stahl et al., 2010).

5. Results and discussion

5.1. Trends in timing and frequency

Findings suggest an increasing frequency of changes in the timing of high-flow events when compared to traditional patterns in the study area. Overall, the timing of spring floods has generally advanced, occurring earlier, whereas autumn high flows now happen at later dates. The coastal region rivers exhibit more prominent trends in this regard; however, in the northernmost part of Finland, these trends have not yet become apparent. The magnitude of floods in Finland has generally diminished over time, leading to extended return periods for floods, with the least common high-flow events occurring before the millennium and low-flow events occurring afterwards. Statistically significant trends in earlier flow peak timing during the spring period were detected at 21 of the 36 studied sites when considering the entire measurement period of each site. The spring high-flow peak times were from 6 to 68 days earlier depending on the time scales considered (Table 3).

In region B, where discharge peaks are high and short in terms of time due to the low number of lakes in the watershed area, the advancing spring high-flow trends on sites were the greatest. In region C, where the northernmost rivers usually freeze in late autumn and the southernmost rivers freeze later on, advancing trends were observed mostly in the southern part of the area on 12 sites (Fig. 4). In region A, where lakes in the watershed areas even the flow fluctuations, some trends of earlier spring flow peaks were found. During autumn, a distinctive trend of delayed high-flow peak timing was evident in region C. The shift occurred at eight out of 36 sites, with the peak taking place 30–60 days later. The most frequent advancements in autumn high flow were observed in the 1-day high-flow values. The rise in 1-day high flows during autumn can be attributed to an increase in the volume of precipitation events occurring as water instead of snow, together with an increase in 1-day extreme precipitation events. Both spring and autumn high-flow timing changes follow similar trends as measured and predicted for other rivers on the same latitudes (Gohari et al., 2022; Matti et al., 2017; Veijalainen et al., 2010) and are even higher compared to previous studies of the regions (Korhonen and Kuusisto, 2010). For 1961–1990, 10 out of 17 sites had for the spring period an advancing trend in flow timing on different day scales, varying from 2 days to 32 days. Similarly, for 1991–2020, eight sites out of 36 had advancing spring high-flow trends, from 15 to 36 days. However, for autumn high flows, there were only a few significant shifting trends towards later timing during both the 1961–1990 and 1991–2020 periods. Even though the later autumn high-flow timing changes were not that evident for the whole study region, the changes in both spring and autumn indicate that the typical flow behaviour has altered. The observed changes can be attributed to the factors of winter-duration shortening, earlier snowmelt timings, and alterations in precipitation patterns (Irannezhad et al., 2014; Veijalainen et al., 2010; Wilson et al., 2010).

Table 3
Annual and cumulative flow peak timing change during the Jan–Jun and Jul–Dec period. Annual and cumulative changes were calculated for the observation period specific to each site. Only statistically significant trends ($p < 0.05$) are listed.

Observation site	Records since	Variable	Annual change (d/yr)	Cumulative change (d)
C2. Haukipudas	1937	Jan–Jun 7-day HQ DoY	-0.1	-10
		Jan–Jun 30-day HQ DoY	-0.1	-10
		Jul–Dec 1-day HQ DoY	0.4	35
		Jul–Dec 3-day HQ DoY	0.5	42
		Jul–Dec 7-day HQ DoY	0.4	33
C3. Hosionkoski	1962	Jan–Jun 1-day HQ DoY	-0.2	-10
		Jan–Jun 3-day HQ DoY	-0.2	-9
		Jan–Jun 30-day HQ DoY	-0.2	-9
		Jul–Dec 1-day HQ DoY	0.5	30
B4. Hyyppä	1966	Jan–Jun 30-day HQ DoY	-0.3	-17
C7. Iso Puutiojärvi (lake outlet)	1975	Jan–Jun 30-day HQ DoY	-0.3	-13
B8. Karkkimala	1972	Jan–Jun 30-day HQ DoY	-0.4	-18
C9. Karunki	1911	Jan–Jun 1-day HQ DoY	-0.1	-12
		Jan–Jun 3-day HQ DoY	-0.1	-12
		Jan–Jun 7-day HQ DoY	-0.1	-13
		Jan–Jun 30-day HQ DoY	-0.1	-7
B10. Kaukolankoski	1970	Jan–Jun 1-day HQ DoY	-0.5	-28
		Jan–Jun 3-day HQ DoY	-0.6	-32
		Jan–Jun 7-day HQ DoY	-0.6	-32
		Jan–Jun 30-day HQ DoY	-0.5	-23
C11. Kilpisjärvi (lake outlet)	1952	Jan–Jun 1-day HQ DoY	-0.1	-10
		Jan–Jun 3-day HQ DoY	-0.1	-10
		Jan–Jun 7-day HQ DoY	-0.1	-8
C13. Konttajärvi (lake outlet)	1985	Jul–Dec 1-day HQ DoY	1.7	60
		Jul–Dec 3-day HQ DoY	1.6	58
A14. Kontturi	1978	Jan–Jun 30-day HQ DoY	-0.3	-13
B15. Köpingsbro	1972	Jan–Jun 30-day HQ DoY	-0.6	-28
B16. Kruunupyy	1993	Jan–Jun 1-day HQ DoY	-0.8	-23
		Jan–Jun 3-day HQ DoY	-1	-28
		Jan–Jun 7-day HQ DoY	-0.9	-25
		Jan–Jun 30-day HQ DoY	-0.7	-19
C17. Livojoki, Hankikoski	1974	Jan–Jun 30-day HQ DoY	-0.2	-8
C21. Naamijoki	1971	Jul–Dec 1-day HQ DoY	1.1	53
C22. Nuorittajoki	1967	Jan–Jun 1-day HQ DoY	-0.2	-11
		Jan–Jun 3-day HQ DoY	-0.4	-22
		Jan–Jun 30-day HQ DoY	-0.3	-15
		Jul–Dec 30-day HQ DoY	0.7	36
A24. Oulankajoki	1966	Jan–Jun 1-day HQ DoY	-0.2	-10
		Jan–Jun 3-day HQ DoY	-0.2	-12
		Jan–Jun 7-day HQ DoY	-0.2	-12
		Jan–Jun 30-day HQ DoY	-0.3	-14
B29. Perus	1970	Jan–Jun 1-day HQ DoY	-0.5	-26
		Jan–Jun 3-day HQ DoY	-0.4	-23
		Jan–Jun 7-day HQ DoY	-0.5	-25
		Jan–Jun 30-day HQ DoY	-0.4	-22
C30. Porkkalan silta	1962	Jan–Jun 1-day HQ DoY	-0.2	-12
		Jan–Jun 3-day HQ DoY	-0.2	-12
		Jan–Jun 7-day HQ DoY	-0.2	-12
		Jan–Jun 30-day HQ DoY	-0.2	-10
		Jul–Dec 1-day HQ DoY	1	59
		Jul–Dec 3-day HQ DoY	0.8	49
		Jul–Dec 7-day HQ DoY	1	62
		Jul–Dec 30-day HQ DoY	0.8	49
B31. Puskamarkki	1985	Jan–Jun 1-day HQ DoY	-0.9	-32
		Jan–Jun 3-day HQ DoY	-0.8	-30
		Jan–Jun 7-day HQ DoY	-0.8	-30
B32. Puttakoski	1970	Jan–Jun 1-day HQ DoY	-0.6	-32
		Jan–Jun 3-day HQ DoY	-0.7	-34
		Jan–Jun 7-day HQ DoY	-0.6	-29
		Jan–Jun 30-day HQ DoY	-1.3	-68
B33. Pyhäjärvi (lake outlet)	1954	Jan–Jun 1-day HQ DoY	-0.3	-23
		Jan–Jun 3-day HQ DoY	-0.4	-24
		Jan–Jun 7-day HQ DoY	-0.4	-25
		Jan–Jun 30-day HQ DoY	-0.4	-26
C34. Simo	1911	Jan–Jun 30-day HQ DoY	-0.1	-6
		Jul–Dec 1-day HQ DoY	0.4	41
		Jul–Dec 3-day HQ DoY	0.3	36

(*continued on next page*)

Table 3 (*continued*)

Observation site	Records since	Variable	Annual change (d/yr)	Cumulative change (d)
		Jul–Dec 7-day HQ DoY	0.3	37
C35. Siuruanjoki, Leuvankoski	1959	Jan–Jun 30-day HQ DoY	-0.2	-12
		Jul–Dec 1-day HQ DoY	0.7	45
		Jul–Dec 3-day HQ DoY	0.7	45
		Jul–Dec 7-day HQ DoY	0.7	43
		Jul–Dec 30-day HQ DoY	0.6	35

From the results, 1991–2000 stood out as the decade when the high-flow events with the highest return periods occurred, whereas the rarest low-flow events occurred during 2001–2010. The rare high-flow events were most frequently observed across the study area during 1971–1980 and 1991–2000 on both 7-day and 30-day scales (Appendix 1). By contrast, the dry seasons were common at the beginning of the 21st century, and the rarest frequencies were on several sites occurring during 2001–2010. Region C experienced the most exceptional high-flow events during 1991–2000. In contrast, similar events in region B were observed during 1971–1980. Both regions B and C encountered the rarest low-flow events during 2001–2010 together with the high-flow event return periods remaining low. In the case of region A, the least-common high-flow events, as well as the rarest low flows, were recorded from 1991 to 2010. Results indicate that the 2001–2010 period was rather dry in all regions and that the rarest return periods followed the occurrence of years with droughts and floods identified before. Similarly, Korhonen and Kuusisto (2010) observed notable drought periods in the

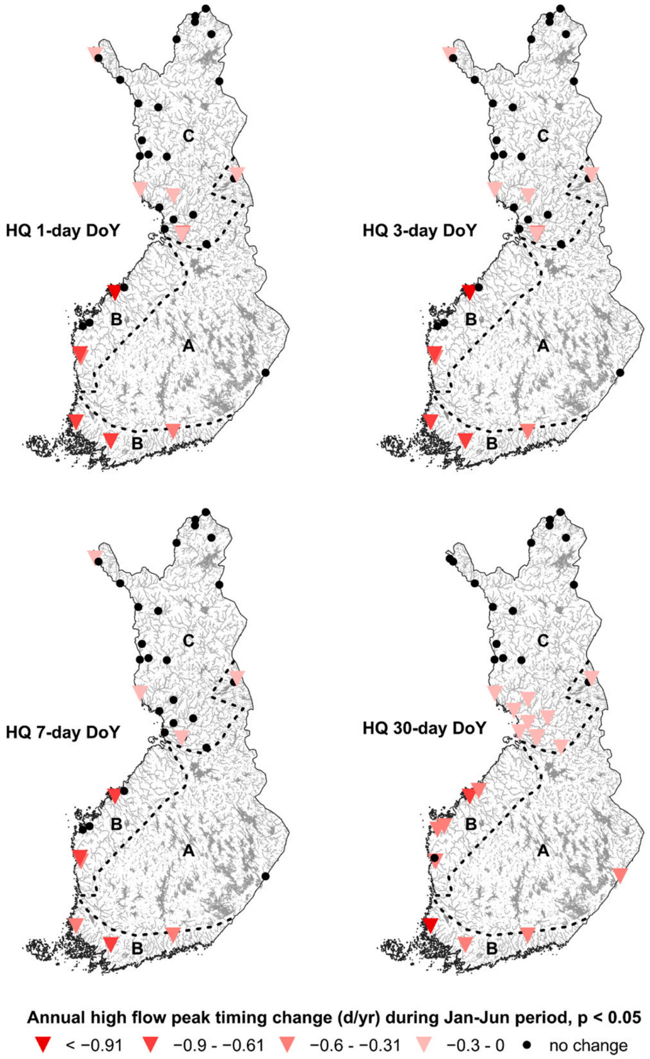

Fig. 4. Annual high-flow peak timing change in days during the Jan–Jun period for all records. Region B shows the most pronounced trends of advancement, whereas in region C, changes are concentrated in the southern part of the area. When comparing various time scales, the occurrence date of the 30-day high-flow period is advancing in the majority of the stations.

years 2002–2003. Additionally, droughts were identified in 1976, particularly in region C, and in 1978 in region B. The findings are also in line with Slater et al.'s (2021) study of global changes in flood return periods, where the return periods of 20-, 50-, and 100-year floods in Finland had increased from the 1970s state. In most of their cases, the return periods of flood had doubled, indicating that the flood magnitudes in Finland have decreased to the present day and, therefore, that the return periods of floods have increased.

In our study, we observed the rarest high-flow events occurring mainly before year 2000, while low-flow events were measured after. Between the 1961–1990 and 1991–2020 climatological periods, increases in annual mean precipitation and annual mean temperature were addressed (Jokinen et al., 2021). The highest recorded precipitation rate was in 2008, and the lowest was in 1941 (Irannezhad et al., 2014). Regarding extreme floods and droughts, decreases in persistent snow cover and snow accumulation reduce the possibility of spring snowmelt-induced extreme flooding, especially in the southern parts of Finland. Despite the increased precipitation, warmer winters and springs result in diminished snow accumulation and the onset of earlier flow events. This results to a reduced likelihood of high-flood events due to diminished spring snowmelt. However, projected high precipitation during winter and spring snowmelt, along with the projected extreme short-term rain events in other seasons, may still contribute to floods (Ruosteenoja and Jylhä, 2021). Several of the least common low-flow occurrences have taken place during the 21st century, in contrast to the frequency of high-flow events. Rising temperatures and extending summers are expected to increase the probability of summer and early autumn drought conditions, leading to decreases in minimum discharges, especially in Southern and Central Finland (Veijalainen et al., 2019). In the future, low-flow event occurrences may increase due to the projected increase in consecutive dry days during the summer season (Lehtonen et al., 2014).

5.2. *Trends in volume and magnitude*

Trends of annual and seasonal flow volumes varied across the different regions. In flow volumes, noteworthy rises were observed in winter months, particularly in region C. Conversely, in region B, there was a notable decline in spring flow volumes. During the entire observation period of each site, three of the 36 sites, all of them in region C, had a statistically significant increasing trend in annual total volume, whereas significant decreasing trends were not found (Table 4). When half-year periods were studied, more patterns were observed. In the Jan–Jun period, an increasing total volume trend was evident at five sites, all situated in region C. Conversely, in region B, one site displayed a decreasing total volume trend during this period. In the Jul–Dec period, increasing volume trends were noted at three sites, all in region C, and a single site in the same region exhibited a decreasing trend. An increase in MQ was observed at

Table 4

Annual changes in whole-year total, half-year total, minimum, mean, and maximum volume (m^3/s) are depicted for both the entire observation period and the 1991–2020 period. Only statistically significant ($p < 0.05$) trends are included, with "+" indicating an increasing trend and "-" a decreasing trend.

		Annual volume change trend (+/-)								
		Whole observation period						**1991–2020**		
Observation site	**Records since**	**Whole year total Q**	**Jan–Jun total Q**	**Jul–Dec total Q**	**NQ**	**MQ**	**HQ**	**NQ**	**MQ**	**HQ**
A12. Kitkajoki, Käylä	1971				+		–			
A14. Kontturi	1978						–			
A24. Oulankajoki	1966								+	
B15. Köpingsbro	1972								+	
B29. Perus	1970		–				–			
B32. Puttakoski	1970				+					
C1. Alaköngäs	1962								+	
C2. Haukipudas	1937					+		+		
C5. Iijärvi (lake outlet)	1951		+			+		+		
C6. Inarijoki, Karigasniemi	1961				+		–			
C7. Iso Puutiojärvi (lake outlet)	1975				–					
C9. Karunki	1911		+	+	+	+	+			
C11. Kilpisjärvi (lake outlet)	1952				–					
C13. Konttajärvi (lake outlet)	1985			–					–	
C17. Livojoki, Hankikoski	1974			+			–		+	–
C20. Muonionjoki, Muonio	1959	+	+			+				
C22. Nuorittajoki	1967					+	–		+	
C23. Onnelansuvanto	1959							+	+	
C25. Ounasjoki, Köngäs	1941		+				+	+		
C26. Ounasjoki, Marraskoski	1919	+			+	+			+	
C28. Pello	1959	+	+	+	+			+	+	
C30. Porkkalan silta	1962						–		+	
C34. Simo	1911				+					

several sites in region C. When considering NQ, sites in region C showed an increasing trend, whereas sites in regions A and B also exhibited varying trends. HQ showed more declining trends than increasing ones, with most of the decreasing trends occurring in region C. During the subperiods of 1961–1990 and 1991–2020, only individual increasing or decreasing trends in annual, Jan–Jun, and Jul–Dec total discharge volumes were identified. A similar pattern emerged for NQ, MQ, and HQ during the 1961–1990 period, without consistent regional trends. However, in the 1991–2020 period, MQ exhibited an increasing trend at nine sites across all regions, whereas only one site in region C displayed a decreasing trend. HQ during the same period showed a decreasing trend in one site in region C. Conversely, for NQ in the 1991–2020 period, five sites, all situated in region C, displayed an increasing trend.

Our results suggest that changing trends of the extreme flow event volumes are more present for the whole observation period in one-third of the sites, whereas mean annual volumes have increased during 1991–2020 in one-quarter of the sites. The previously mentioned changes are mainly present in region C. Blöschl et al. (2019) observed trends of flood discharges in Europe from 1960 to 2010, reporting a decrease in flood discharges in most parts of Finland on a decadal scale, particularly in Southern Finland. The decreasing trends of HQ found in this study follows the previously found changes and contributes to similar findings of HQ increases and decreases regionally in Finland. However, Blöschl et al. (2019) found some increasing flood trends in Ounasjoki, Tana, and Torne watershed areas, but these trends were not statistically significant ($p < 0.1$). In this study, statistically significant ($p < 0.05$) increasing HQ trends were present on C9. Karunki, and C25. Ounasjoki, Köngäs stations, located in Torne and Ounasjoki watersheds.

Monthly volume trends were computed for each site using the same time-period structure employed for annual volume data. Over the entire observation period, changes in monthly mean flow volumes were observed for 30 out of the 36 monitored sites (Table 5). On five of the sites, only decreasing monthly trends were found, on 15 sites only increasing trends, and on 10 sites both increasing and decreasing. In region A, a decrease in monthly flow volumes was noted for June, whereas an increase was observed in the early spring months. For autumn, both increasing and decreasing trends were identified. When examining the results for regions B and C, clear trends emerged across these areas. In region B, a declining trend in spring month flow volumes was observed for nearly all sites, whereas in region C, fewer sites exhibited decreasing trends in spring month flow volumes. Conversely, increasing trends were evident in region C for monthly flow volumes during the autumn, winter, and spring months. In general, the observed trends suggest there are

Table 5

Monthly mean discharge volume trends, organized by region for all observation years. Only statistically significant ($p < 0.05$) trends are depicted, with "+" indicating an increasing trend and "-" a decreasing trend. Volume trends underwent the most notable changes in spring, especially in April at the study sites, whereas the volumes remained relatively stable during the summer months.

Observation site	J	F	M	A	M	J	J	A	S	O	N	D
A12. Kitkajoki, Käylä			+	+								
A14. Kontturi						–				–		
A24. Oulankajoki		+				–					+	
B4. Hyyppä					–							
B8. Karkkimala					–							
B10. Kaukolankoski				–	–							
B15. Köpingsbro		+			–							
B16. Kruunupyy						–					+	
B29. Perus				–	–						+	
B32. Puttakoski				–	–							
C1. Alaköngäs				+								
C2. Haukipudas				+	–							
C3. Hosionkoski	+	+	+	+							+	+
C5. Iijärvi (lake outlet)	+	+	+	+	+							+
C6. Inarijoki, Karigasniemi		+	+	+								
C7. Iso Puutiojärvi (lake outlet)				+		–			–			
C9. Karunki	+	+	+	+	+						+	+
C13. Konttajärvi (lake outlet)				+				–	–			
C17. Livojoki, Hankikoski				+							+	+
C18. Lutto	+											
C19. Muonionjoki, Kaaresuvanto		+										
C22. Nuorittajoki	+	+	+	+	–						+	+
C23. Onnelansuvanto			+									
C25. Ounasjoki, Köngäs				+	+							
C26. Ounasjoki, Marraskoski			+	+	+						+	
C27. Peerajärvi (lake outlet)	+	+	+	+			+					+
C28. Pello	+	+	+	+	+		+			+	+	
C30. Porkkalan silta				+	–							+
C34. Simo	+	+	+	+	–	–						
C35. Siuruanjoki, Leuvankoski		+	+	+							+	+

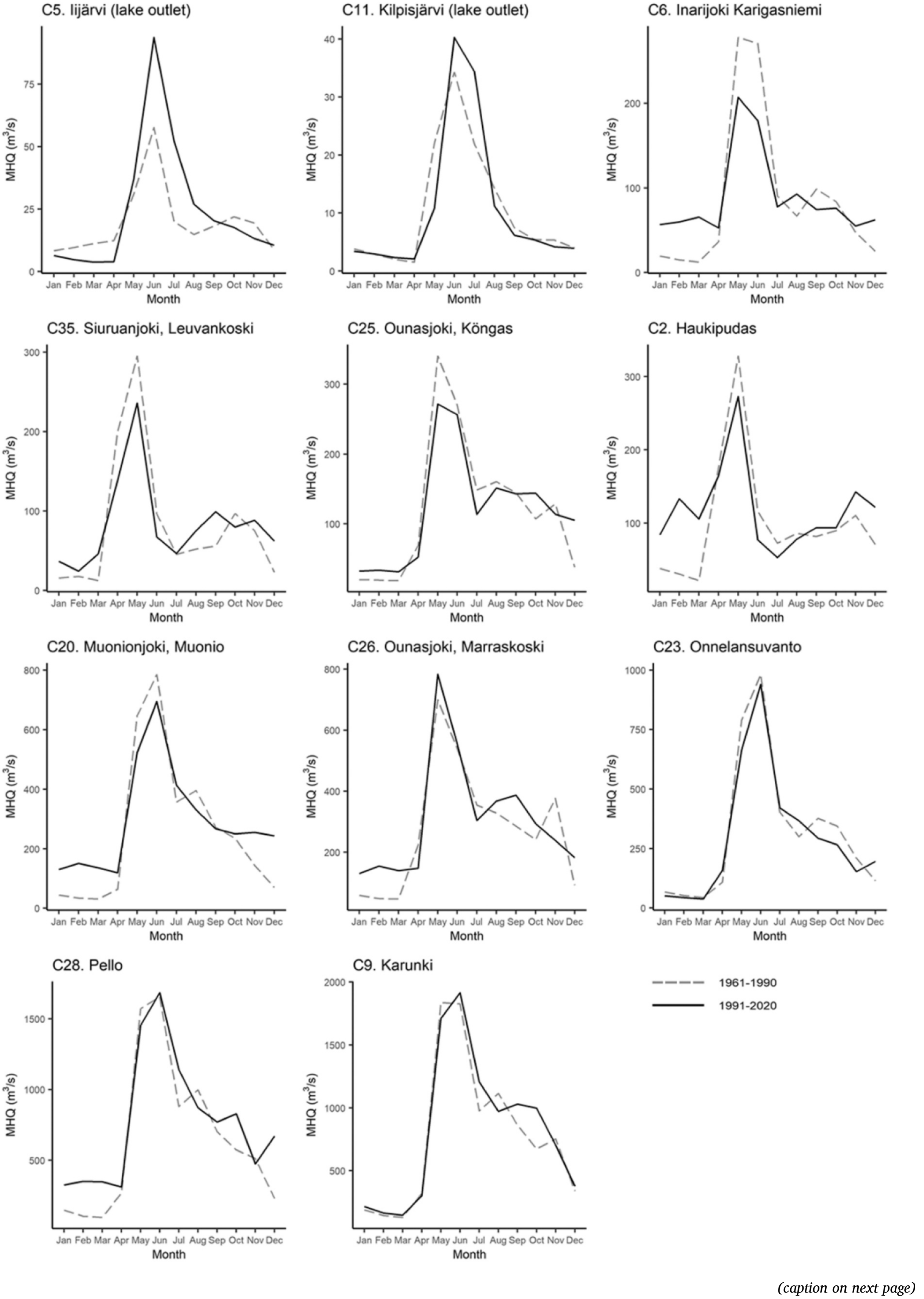

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Fig. 5. Comparison of monthly mean high discharges for the periods 1961–1990 and 1991–2020 in region C. Note the increases in the autumn and winter MHQ values (presented with a solid line) on the 1991–2020 period. The scale on the y-axis varies according to the discharge scale of the respective site.

increases in monthly volumes earlier in the spring and throughout the late autumn and winter months. This results in earlier occurrences of spring high discharges and an overall increase in mean volumes during late autumn and winter across Finland.

During the period from 1961 to 1990, noticeable monthly trends in mean values were predominantly observed in the spring months, suggesting a shift towards earlier spring flooding. In the subsequent period from 1991 to 2020, the previously mentioned spring trend persisted, and trends in late autumn and winter months showed an increase in mean values. When considering the monthly high flows between these two periods, high-flow volumes in the spring months decreased and higher autumn and winter flows increased in many of the sites in the later period (Fig. 5), indicating that previously noted changes in monthly volumes have occurred during the 1991–2020 period. Previous studies have validated the trend of rising flow volumes in late winter and early spring months (Korhonen and Kuusisto, 2010), alongside a decline in late spring and early summer months, signalling earlier snowmelt and effects of climate change (Blöschl et al., 2017). In the Nordic region, this increase in flow volume during winter and spring has been explained by the warm and wet period, which started around the year 1990 (Wilson et al., 2010). Between the 1961–1990 and 1991–2020 periods, precipitation increased in Finland by 9% together with a 1.3 °C increase in mean temperature (Jokinen et al., 2021). The most significant increase in precipitation was noted during December, January, and February, aligning with the identified trend of higher flow volumes during these same months found in this study.

Flow magnitudes were examined from high- and low-flow volumes on 1-, 3-, 7-, and 30-day scales. For the whole observation period of each station, nine sites from all three regions had a decreasing trend of high-flow magnitude on different day scales, and decreases varied from less than 0.1 m^3/s to 3.2 m^3/s annually. In region C on three sites (Karunki, Ounasjoki – Marraskoski, and Ounasjoki – Köngäs), there was an observed rise in flow magnitudes, consistent with the observations of Blöschl et al. (2019). For the Jan–Jun period, 11 out of all 36 sites had decreasing trends, and three had increasing flow magnitude trends for the whole year, but the change magnitudes were larger (Fig. 6). In the Jul–Dec period, high-flow magnitudes increased in seven sites and decreased in one site (Kitkajoki). As for the low-flow magnitude, for the whole time period, 11 sites had increases in low-flow event magnitudes, and three saw decreases, whereas on the Jan–Jun scale, 12 sites had increases and four saw decreases (Fig. 7). For the Jul–Dec period, five sites had an increasing trend and five saw decreasing low-flow event trends.

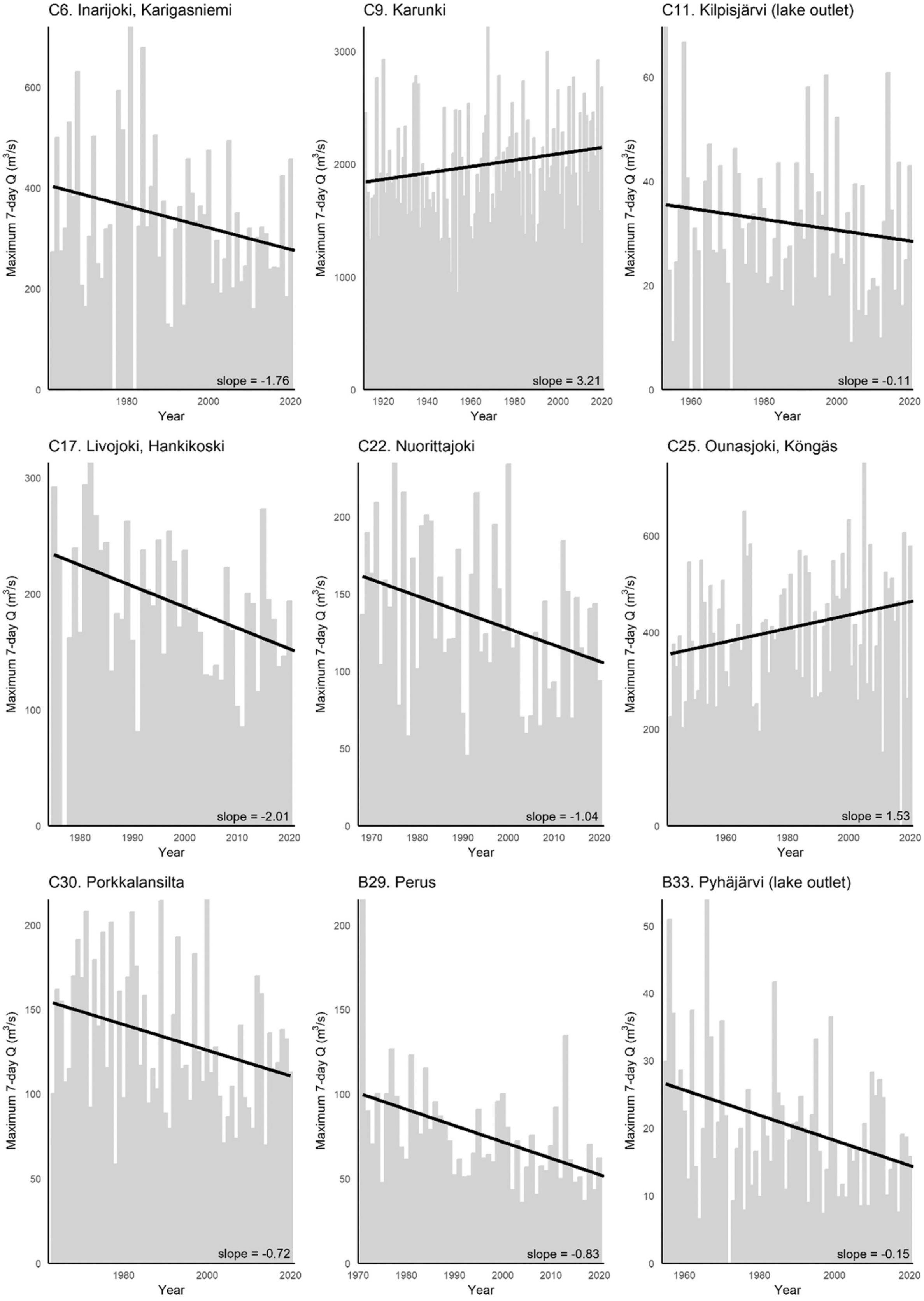
For the 1961–1990 and 1991–2020 spring periods, only a few annual trends were detected. In the 1961–1990 autumn period, a decline in daily high-flow magnitudes was observed in two sites (Iijärvi and Inarijoki-Karigasniemi). However, in the subsequent period from 1991 to 2020, a similar trend of decreasing high-flow magnitudes was identified at five sites, all within region C. Regarding low-flow magnitudes in the springtime during the 1961–1990 period, reductions were recorded at two stations (Kilpisjärvi and Patoniva). In contrast, from 1991 to 2020, low-flow magnitudes displayed an increase at seven stations, with annual variations ranging from 0.1 m^3/s to 1.5 m^3/s. For autumn low flows, during the 1961–1990 period, there was a decrease at five stations. However, in the subsequent period from 1991 to 2020, autumn low flows exhibited an increase at five stations, all of which were located in region C.

Similar trends in spring flow magnitudes were found in the latest study of the same region (Gohari et al., 2022), whereas earlier studies had not addressed these changes in the spring flow magnitudes (Korhonen and Kuusisto, 2010). However, increases in spring flood magnitude in Northern Finland and decreases in Southern Finland have been predicted to occur in climate scenario studies (Olsson et al., 2015; Veijalainen et al., 2012). In our results, the decreases were already present in the southern part of region C, whereas the increases in the spring flow volume were present in some of the northern sites of the region. High snowmelt rates induce high-magnitude flow events, but as a result of climate warming, slower spring snowmelt has been measured (Wu et al., 2018; Musselman et al., 2017). As spring snowmelt is divided into longer periods, similarly, flow magnitudes have declined. Vormoor et al. (2015) predicted that, in Norwegian catchments, autumn and winter floods become more significant in the future and that some flood events could shift from typical snowmelt-induced spring floods to autumn when rain replaces snowmelt as the prevailing flood driving factor.

6. Conclusions

This study enhances the knowledge of long-term changes in hydrological variables of Finnish unregulated rivers, offering new insights beyond previous research and surpassing the scope of previous studies. The analyses included daily discharge measurements throughout the entire observation period of each station and for the specific climatological normal periods of 1961–1990 and 1991–2020, whenever possible. Comparison of discharges between two climatological normal periods contributes to understanding the effects of climate change on the present discharge regime in Finland.

Traditionally, the most significant flow peaks in Finland generally occurred during spring and early summer, depending on specific



C6. Inarijoki, Karigasniemi

C9. Karunki

C11. Kilpisjärvi (lake outlet)

C17. Livojoki, Hankikoski

C22. Nuorittajoki

C25. Ounasjoki, Köngäs

C30. Porkkalansilta

B29. Perus

B33. Pyhäjärvi (lake outlet)

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Fig. 6. Statistically significant 7-day high-flow volume trends in the Jan–Jun period, calculated for the whole observation period of each site. The most significant trends ($p < 0.05$) are presented. The y-axis scale varies based on the discharge scale, whereas the x-axis scale corresponds to the observation period of the respective site.

geographical locations, and were caused by spring snowmelt. In Southern Finland, high flows driven by high amounts of precipitation were also possible during other seasons. The findings of this study reveal changing patterns in discharge volumes, magnitudes, and the timing and frequency of high and low-flow events. When considering the entire timespan of the discharge measurements, high-flow magnitudes are decreasing in nearly one-third of the studied sites and low-flow magnitudes are increasing in one-third of the sites. On monthly scale, low-flow magnitudes are increasing during late autumn, winter and early spring months, while high-flow magnitudes decreasing in late spring months. Flow magnitudes generally increase during early spring and late winter months and decrease in late spring and early summer. Following the detected changes in flow magnitudes, also spring high-flow events occur earlier across

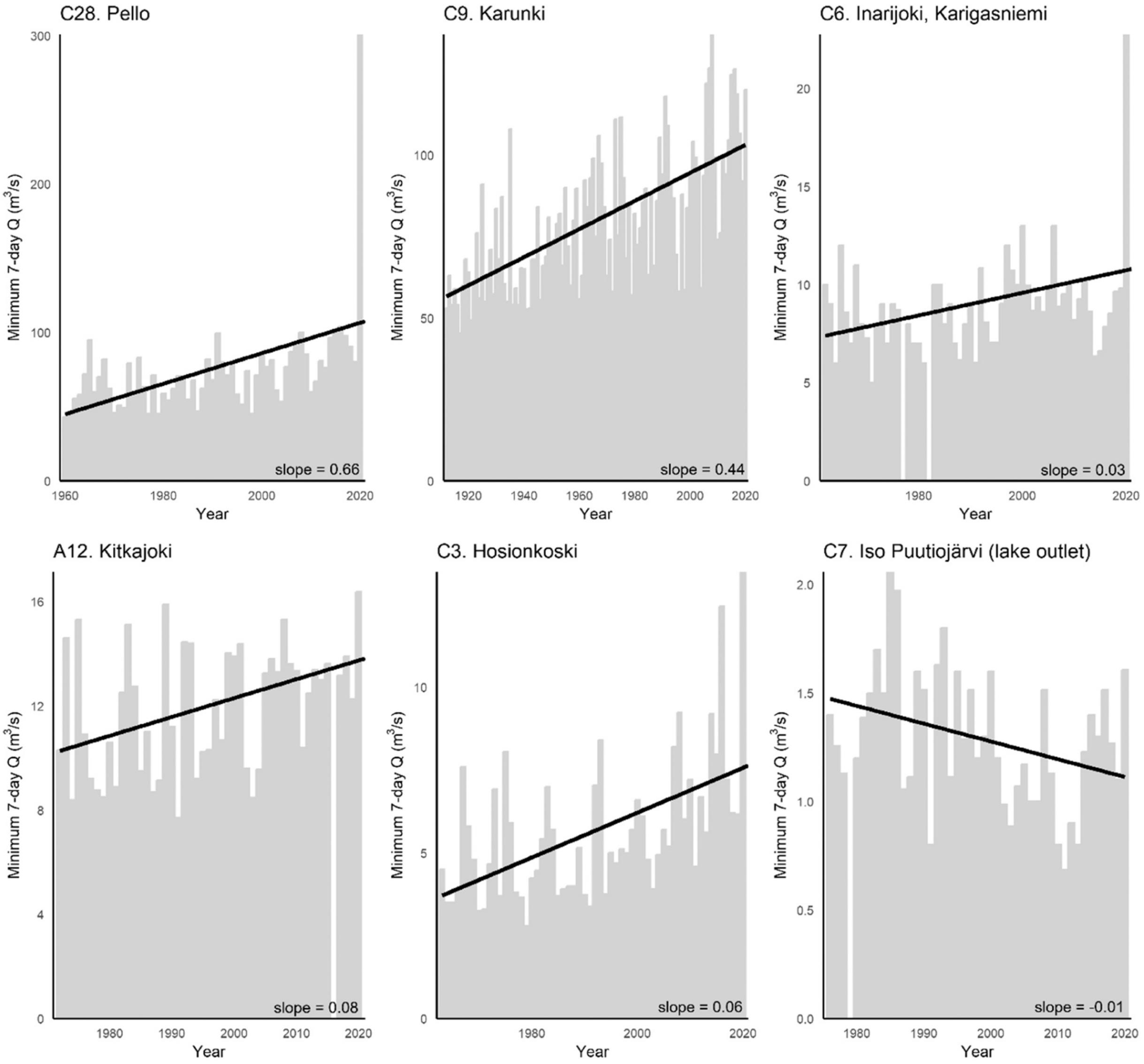

Fig. 7. Statistically significant 7-day low-flow volume trends in the Jan–Jun period, calculated for the whole observation period of each site. The most significant trends ($p < 0.05$) are presented. The y-axis scale varies based on the discharge scale, whereas the x-axis scale corresponds to the observation period of the respective site.

Finland. The analysis suggests that rare high-flow events were more likely to occur during the periods 1971–1980 and 1991–2000, while the rarest low-flow events were predominantly observed during 2001–2010. Despite increased precipitation in Finland and warmer winters and springs due to rising temperatures, there is less snow accumulation and earlier flow events, aligning with an earlier spring onset. This reduction in spring snowmelt diminishes the observed likelihood of high-flood events, decreasing the frequency of extreme high flow events.

Notably, a greater number of change trends were observed during the 1991–2020 period, particularly when comparing it with the earlier period. For the 30-year periods used in this study, prior research has identified increases in both mean temperature and precipitation in Finland. Despite an overall increase in precipitation, rises in annual total volumes were noted only at a limited number of sites. Conversely, increases in minimum, mean, and maximum flow volumes were noted in this study. The findings suggest that, even though spring flow peaks are on the decline, there is a redistribution of flow volumes to other periods. This underscores the complexity of hydrological patterns, emphasizing the necessity to not only focus on total volumes but also consider their temporal distribution. The regional aspect considered in this study revealed more pronounced changes in the coastal region watersheds than in others. A comprehensive understanding of the flow regime requires considering the timing, frequency, volume, and magnitude of flow events across various periods. This study conducted such an analysis to attain a broader understanding of the current situation, gain insights into possible future scenarios, and perhaps provide policymaking information for water resource management and environmental planning.

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CRediT authorship contribution statement

Petteri Alho: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Cintia Bertacchi Uvo:** Writing – review & editing. **Elina Kasvi:** Writing – review & editing, Supervision, Conceptualization. **Karoliina Lintunen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The discharge data used in this study are publicly available from the Finnish Environment Institute Hertta database.

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Appendix

Table A1
Highest return periods in years of 7-day and 30-day high and low flow events per decade.

		Highest return period (years) of 7-days high flow event									
Station	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C1. Alaköngäs						54	27	4	5	8	4
C2. Haukipudas			2	5	85	9	17	21	43	3	5
C3. Hosionkoski						8	20	30	59	5	12
B4. Hyyppä						17	50	13	25	7	6
C5. Iijärvi (lake outlet)					14	11	6	1	6	56	28
C6. Inarijoki, Karigasniemi						30	59	20	15	2	10
C7. Iso Puutiojärvi (lake outlet)							5	43	22	6	5
B8. Karkkimala							46	15	9	8	4
C9. Karunki	36	4	18	6	7	109	22	12	55	16	27
B10. Kaukolankoski							15	22	44	9	11
C11. Kilpisjärvi (lake outlet)					65	8	7	6	16	3	22
A12. Kitkajoki, Käylä							49	25	7	4	5
C13. Konttajärvi (lake outlet)								3	31	4	10
A14. Kontturi							2	44	22	3	6
B15. Köpingsbro							45	23	9	4	8
B16. Kruunupyy									22	11	7
C17. Livojoki, Hankikoski							16	47	7	3	12
C18. Lutto									24	8	4
C19. Muonionjoki, Kaaresuvanto						60	10	30	7	9	15
C20. Muonionjoki, Muonio							50	25	13	3	8
C21. Naamijoki							25	4	50	5	13
C22. Nuorittajoki						6	55	9	28	3	5
C23. Onnelansuvanto						32	16	21	13	8	63
A24. Oulankajoki						3	27	11	14	8	54
C25. Ounasjoki, Köngäs				6	7	40	3	10	27	80	20
C26. Ounasjoki, Marraskoski		6	51	11	6	6	20	4	26	102	34
C27. Peerajärvi (lake outlet)						9	19	5	57	4	29
C28. Pello					1	63	11	9	32	16	21
B29. Perus							52	10	7	3	26
C30. Porkkalan silta						7	20	30	59	3	5
B31. Puskamarkki								5	11	7	34
B32. Puttakoski							7	24	48	5	8
B33. Pyhäjärvi (lake outlet)					33	66	4	22	11	6	5
C34. Simo		101	51	10	7	13	34	20	25	4	6
C35. Siuruanjoki, Leuvankoski					1	8	11	32	63	5	6
C36. Utsjoki, Patoniva						11	27	8	54	9	6

	Highest return period (years) of 30-days high flow event										
	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C1. Alaköngäs						54	5	14	27	18	2
C2. Haukipudas			3	21	85	8	43	28	9	3	14
C3. Hosionkoski						6	30	59	15	3	12
B4. Hyyppä						17	50	8	25	5	10
C5. Iijärvi (lake outlet)					9	11	4	2	18	28	55
C6. Inarijoki, Karigasniemi						20	59	30	10	12	7
C7. Iso Puutiojärvi (lake outlet)							6	43	14	5	11
B8. Karkkimala							46	23	8	5	15
C9. Karunki	27	6	14	3	7	11	109	16	55	18	22
B10. Kaukolankoski							6	44	22	9	7
C11. Kilpisjärvi (lake outlet)					65	8	9	5	33	3	7
A12. Kitkajoki, Käylä							49	25	7	3	4
C13. Konttajärvi (lake outlet)								3	31	5	10
A14. Kontturi							2	22	44	3	4
B15. Köpingsbro							23	45	8	5	11
B16. Kruunupyy									22	6	11
C17. Livojoki, Hankikoski							12	47	8	3	16
C18. Lutto									24	12	4
C19. Muonionjoki, Kaaresuvanto							17	25	50	10	6
C20. Muonionjoki, Muonio						20	7	12	60	30	8
C21. Naamijoki							25	4	17	8	50
C22. Nuorittajoki						4	28	55	11	3	8
C23. Onnelansuvanto						32	5	13	21	16	63
A24. Oulankajoki						4	54	9	14	4	27
C25. Ounasjoki, Köngäs				3	40	10	7	20	27	80	16
C26. Ounasjoki, Marraskoski		6	11	4	15	17	20	9	26	102	51
C27. Peerajärvi (lake outlet)					1	29	10	57	19	6	3
C28. Pello					1	7	21	8	63	16	13
B29. Perus							52	26	6	4	5
C30. Porkkalan silta						7	59	30	8	3	12
B31. Puskamarkki								5	34	11	7
B32. Puttakoski							8	24	48	10	4
B33. Pyhäjärvi (lake outlet)					22	66	4	17	7	6	5
C34. Simo	101	6	13	25	51	7	34	14	20	2	10
C35. Siuruanjoki, Leuvankoski					1	6	32	63	11	3	16
C36. Utsjoki, Patoniva						27	7	6	54	14	2

	Highest return period (years) of 7-days low flow event										
	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C1. Alaköngäs						7	9	18	14	54	2
C2. Haukipudas			2	85	43	12	5	8	6	28	4

(*continued on next page*)

Table A1 (*continued*)

	Highest return period (years) of 7-days low flow event										
	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C3. Hosionkoski						20	30	4	10	59	4
B4. Hyyppä						25	10	4	13	50	17
C5. Iijärvi (lake outlet)					28	56	19	2	4	6	5
C6. Inarijoki, Karigasniemi						20	15	59	5	6	5
C7. Iso Puutiojärvi (lake outlet)							3	2	7	43	22
B8. Karkkimala							12	46	4	3	23
C9. Karunki	109	55	14	36	8	4	7	4	6	5	2
B10. Kaukolankoski							44	11	4	22	6
C11. Kilpisjärvi (lake outlet)					2	2	3	65	16	6	4
A12. Kitkajoki, Käylä							25	10	49	16	3
C13. Konttajärvi (lake outlet)								3	8	31	10
A14. Kontturi							2	11	22	44	7
B15. Köpingsbro							23	15	45	8	3
B16. Kruunupyy									6	22	11
C17. Livojoki, Hankikoski							24	47	7	16	9
C18. Lutto									24	6	12
C19. Muonionjoki, Kaaresuvanto						5	12	15	3	60	30
C20. Muonionjoki, Muonio							8	10	7	50	17
C21. Naamijoki							25	50	17	5	4
C22. Nuorittajoki						14	55	28	5	18	6
C23. Onnelansuvanto						32	6	11	8	63	3
A24. Oulankajoki						5	7	27	18	11	8
C25. Ounasjoki, Köngäs				80	16	9	40	13	27	7	2
C26. Ounasjoki, Marraskoski		17	15	34	26	9	102	51	4	3	1
C27. Peerajärvi (lake outlet)						8	11	57	7	14	2
C28. Pello					63	11	21	9	32	6	2
B29. Perus							3	10	7	26	52
C30. Porkkalan silta						59	5	30	15	20	7
B31. Puskamarkki								17	9	34	11
B32. Puttakoski							8	3	10	24	48
B33. Pyhäjärvi (lake outlet)					22	7	66	9	6	33	6
C34. Simo	3	20	51	101	8	10	13	7	3	9	2
C35. Siuruanjoki, Leuvankoski					7	32	9	21	13	63	11
C36. Utsjoki, Patoniva						2	7	27	54	18	2

	Highest return period (years) of 30-days low flow event										
	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C1. Alaköngäs						11	14	18	9	54	2
C2. Haukipudas			9	85	43	11	6	12	7	28	4

(*continued on next page*)

Table A1 (*continued*)

	Highest return period (years) of 30-days low flow event										
	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2021
C3. Hosionkoski						20	30	7	10	59	5
B4. Hyyppä						25	13	8	17	50	5
C5. Iijärvi (lake outlet)					28	55	18	2	4	6	5
C6. Inarijoki, Karigasniemi						15	59	20	30	3	12
C7. Iso Puutiojärvi (lake outlet)							4	3	4	43	22
B8. Karkkimala							46	15	23	7	3
C9. Karunki	109	55	14	36	8	4	7	3	6	5	2
B10. Kaukolankoski							22	11	4	44	5
C11. Kilpisjärvi (lake outlet)					1	4	6	65	16	7	4
A12. Kitkajoki, Käylä							25	10	49	16	3
C13. Konttajärvi (lake outlet)								4	10	31	16
A14. Kontturi							6	15	22	44	4
B15. Köpingsbro							8	23	45	4	3
B16. Kruunupyy									6	22	11
C17. Livojoki, Hankikoski							24	47	9	12	16
C18. Lutto									24	6	12
C19. Muonionjoki, Kaaresuvanto							8	10	7	50	17
C20. Muonionjoki, Muonio						6	15	12	3	60	30
C21. Naamijoki							17	50	25	5	4
C22. Nuorittajoki						18	28	55	6	11	4
C23. Onnelansuvanto						32	8	11	9	63	3
A24. Oulankajoki						8	5	54	18	11	7
C25. Ounasjoki, Köngäs				80	16	10	40	11	27	7	2
C26. Ounasjoki, Marraskoski		17	15	51	34	9	102	26	4	3	2
C27. Peerajärvi (lake outlet)					11	6	14	57	6	19	2
C28. Pello					63	32	13	9	16	6	2
B29. Perus							9	17	7	26	52
C30. Porkkalan silta						30	15	8	20	59	5
B31. Puskamarkki								34	11	17	6
B32. Puttakoski							4	4	12	48	3
B33. Pyhäjärvi (lake outlet)					17	9	66	6	5	33	7
C34. Simo	4	14	34	101	10	9	7	7	5	11	3
C35. Siuruanjoki, Leuvankoski					6	21	11	32	9	63	13
C36. Utsjoki, Patoniva						2	8	18	54	27	2

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