BOREAL ENVIRONMENT RESEARCH 30: 163–179
ISSN 1797-2469 (online)

Helsinki 22 October 2025

Precipitation-Flow Frequency Analysis in Nordic Catchments

Sahand Ghadimi[1)]*, Navid Yaraghi[2)], Nasim Fazel[3)],
Mohammad Reza Nikoo[4)], Björn Klöve[1)] and Ali Torabi Haghighi[1)]

[1)] *Water, Energy and Environmental Engineering Research Unit, University of Oulu, FI90014, Oulu, Finland*
[2)] *Geography Research Unit, University of Oulu, FI90014, Oulu, Finland*
[3)] *Finnish Environment Institute (SYKE), Latokartanonkaari 11, 00790, Helsinki, Finland*
[4)] *Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman*
**corresponding author's e-mail: sahand.ghadimi@oulu.fi*

Received 21 Jan. 2025, final version received 13 Aug. 2025, accepted 15 Aug. 2025

Ghadimi S., Yaraghi N., Fazel N., Nikoo M.R., Klöve B. & Haghighi A.T. 2025: Precipitation-Flow Frequency Analysis in Nordic Catchments. *Boreal Env. Res.* 30: 163–179.

This study assesses precipitation and flow frequencies in two Finnish catchments, Pyhäntä and Ounasjärvi-luusua, using the Generalized Extreme Value (GEV) distribution applied to annual and monthly maxima over two 30-year periods. In Pyhäntä, annual precipitation extremes increased by 42% in the second period, while in Ounasjärvi-luusua, the increase was limited to return periods < 5 years (11%). Conversely, annual flow return levels rose by 48% in Ounasjärvi-luusua, but only for 2–13-year return periods in Pyhäntä. Monthly results showed unclear impacts of summer precipitation extremes and intensive drainage on corresponding flow extremes. A new index (θ) was introduced to describe the linear relationship between precipitation and flow return levels. θ for May–July closely matched annual θ, suggesting summer flows are influenced by snowmelt in Nordic regions. The study highlights that frequency analysis with limited data entails increasing uncertainty with higher return periods, particularly those exceeding the observational record.

Introduction

Due to the unique climate of the Nordic environment, river regimes in Nordic watersheds are affected by unique seasonality consisting of two snow and rainfall-dominant seasons (Matti *et al.* 2017; Ul Hassan *et al.* 2019; Veijalainen *et al.* 2010; Wilson *et al.* 2010). This seasonality, coupled with climate variation (IPCC 2022) and extensive anthropogenic activities such as forest harvesting, may have impacted the severity and frequency of extreme events over time (Gohari *et al.* 2022; Lundin 1994; Walsh *et al.* 2020; Wei *et al.* 2022). On the one hand, global warming has caused more intense precipitation, runoff regime alteration, and shifting snow melt seasonality at higher latitudes. On the other hand, local human activities in catchment areas, like forest management, have increased the frequency of such events (Dyrrdal *et al.* 2013; Schnorbus & Alila 2013). Such variation in extreme events may cause severe damage to connected societies and the environment, affecting erosion and sediment transport regimes, water quality, harming aquatic habitats, increasing infrastructure vulnerability, disrupting forestry practices, threatening energy production, and adding uncertainties to adaptation and mitigation plans (Albrecht 2023; Gohari *et al.* 2022; Kundzewicz 2019; Lintunen *et al.* 2023). Hence, conducting frequency anal-

Editor in charge of this article: Hannu Marttila
https://doi.org/10.60910/ber2025.wopg-t544

ysis under changing climate and land cover, considering different non-stationarity drivers, is a crucial step toward taking mitigative and adaptive actions and policies against the consequent damages of intensifying hydrological extremes.

The frequency of extreme flows in cold climate and snow-dominated regions has been addressed for different purposes such as evaluating long-term variation of floods and summer droughts (Hisdal *et al.* 2006; Matti *et al.* 2016), assessing the impact of climate change on design floods (Lawrence 2020; Lawrence *et al.* 2012; Veijalainen & Vehviläinen 2008), and analyzing flood damage (Hailemariam & Alfredsen 2023). Many studies have found that the frequency of large rainfall and flood events increased over the past decades in the subarctic, especially over Norway, Sweden, and Finland (Lawrence *et al.* 2012; Lehner *et al.* 2006; Matti *et al.* 2016 2017; Vormoor *et al.* 2016; Walsh *et al.* 2020), however, these changes significantly varied between regions. Vormoor *et al.* (2016) observed an increase in flood frequency in the southern and western parts of Norway due to increased rainfall extremes, while snow-dominant floods decreased in northern parts. Matti *et al.* (2016) detected increasing trends in high return periods in Övre Abiskojåkk catchment in Norway. Walsh *et al.* (2020) reported an increase in the frequency of extreme rainfalls of the 95th percentile over Finland and northern Russia. Some studies have also predicted more frequent large floods in the future, with climate models projecting that the typical 100-year floods could become more common in northern Europe, including Finland and Sweden (Lehner *et al.* 2006).

River flow regimes in Northern Europe and the subarctic region are mainly featured by snow-driven seasonality in which annual peak flows occur in early spring and a second but lower peak in the late summer (Arheimer & Lindström 2015; Gohari *et al.* 2022; Osuch *et al.* 2022; Veijalainen *et al.* 2010). In some cases like southern Finland catchments, a rainfall-dominated annual maximum flood is also common (Lintunen *et al.* 2023). In addition to changes in magnitude and frequency, climate change can cause interannual shifts in extreme flows, transitioning from snow-dominant to rainfall-dominant flows (Brunner & Fischer 2022; Gohari *et al.* 2022; Matti *et al.* 2016; Veijalainen 2012). While many studies have addressed the seasonal shifts in peak flows, fewer have addressed the impact of such shifts on the return periods. Dahlke *et al.* (2012) observed earlier and larger peak flow occurrences in two sub-arctic catchments in Sweden. Gohari *et al.* (2022) found complexity in annual peak flows due to earlier and slower snowmelt. In another study, peak flows in March–June and July–September were separated todistinguish long-term flood alteration (Arheimer& Lindström 2015).

For catchments or unregulated headwaters, design flood estimates are frequently required for hydraulic infrastructure design (Instanes *et al.* 2016). Although the flood frequency in the Nordic climate has been studied in different scales, including national (Kobierska *et al.* 2018) and regional or large basin scales (Engeland *et al.* 2020; Thorarinsdottir *et al.* 2018), few studies like Koskela & Linjama (2015) and Johnson & Alila (2023) addressed the issue at catchment level. Moreover, as most of the boreal catchments are covered by forests, the impact of management practices like drainage systems and the related harvesting activities, which are expected to increase the return levels (Kura *et al.* 2012), are not well addressed, especially in Nordic region. Koskela & Linjama (2015) conducted a flood frequency analysis in small forested and agricultural catchments to estimate the design of floods with a return period of 20, 100, and 250 years. Kura *et al.* (2012) aimed to examine the isolated and combined impact of forest management activities (roads and harvesting) on extreme flows in a snow-dominated catchment and found that large events become 5–6.7 times more frequent after harvesting. Johnson & Alila (2023) presented a nonstationary paired watershed approach to analyze the impact of forest harvesting on floods in two nested watersheds and found that forest harvesting can lead to an increase in flood magnitudes, particularly for smaller, more frequent events. Besided the frequency alteration of extreme events, few studies have addressed the relationship between rainfall and flood return levels. This relationship has been explored in large catchments in Greece (Vangelis *et al.* 2022) and Austria (Breinl *et al.* 2021), it has not been applied to small-scale

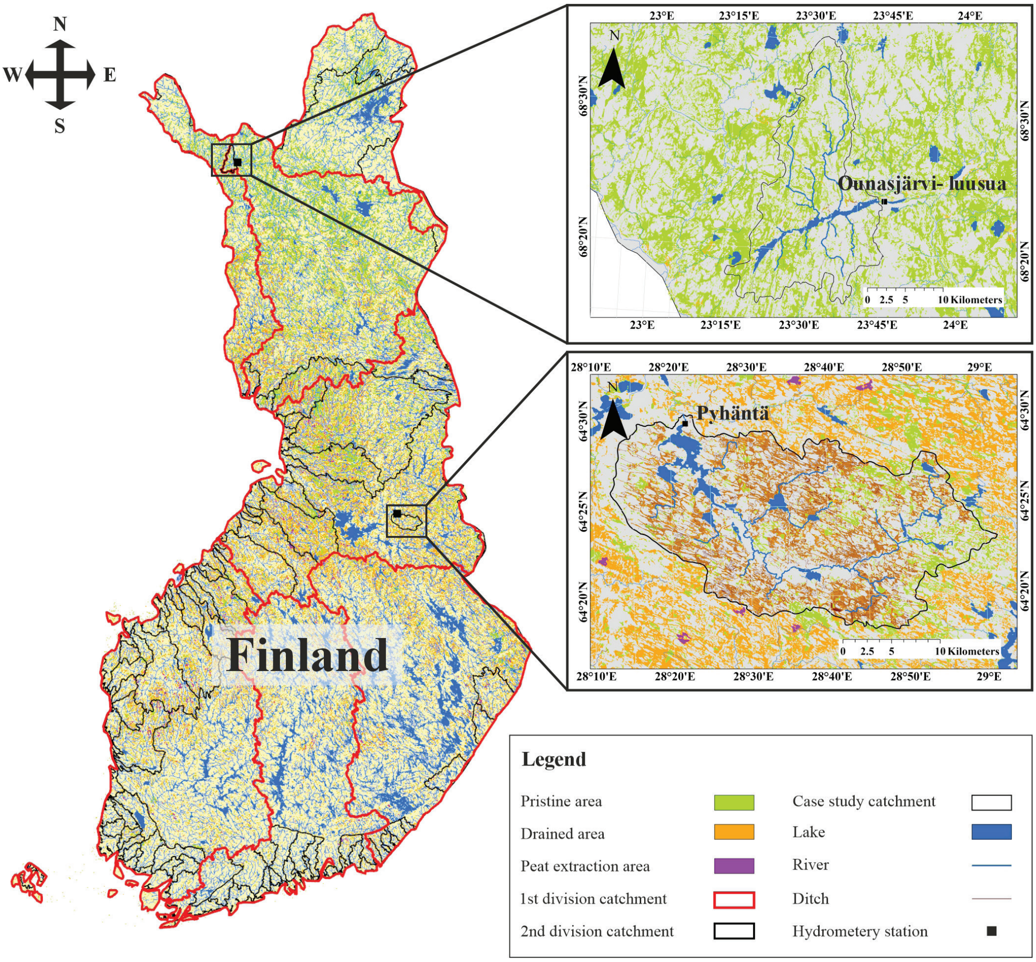

Fig. 1. The location of the two selected catchments, Pyhäntä and Ounasjärvi-luusua in Finland.

catchments in cold climate regions with snow melt dominant flows.

The primary motivation for this study is the combined impact of the unique climate in the Nordic region and northern Scandinavia, along with anthropogenic activities, on river regime components, particularly extreme flow events. The goal is to assess the frequency changes of flow and precipitation extremes in two Finnish catchments: one pristine and one heavily drained. The possible alterations are discussed based on the drainage development decadal milestones from the 60s, considering the observations, assumptions, and data availability in this study. Therefore, the time series of annual and monthly flow and precipitation extremes were divided in two periods of 30 (1961–1990) and 31 (1991–2021) years. Then, the frequency of these extremes is estimated by fitting the Generalized Extreme Value (GEV) distribution and maximum likelihood parameter estimator to the annual and monthly maximums. Moreover, the possible shifts in the precipitation- flow return levels relationships are addressed by defining a new index, called θ, to introduce a new point of view toward the frequency variation.

Material and methods

Study area

The cases for this study (Fig. 1) were selected based on available flow and precipitation record length in two case studies with similar discharge magnitude range, lake area percentage, and catchment area, also different land use and geographical zones. Considering all of these criteria, Pyhäntä and Ounasjärvi-luusua were selected based on the flow station and catchment information obtained from national environmental information database HERTTA (https://www.syke.fi/fi-FI/Avoin_tieto/Ymparistotietojarjestelmat) and the Peatland Drainage Status map from the national environmental institute's (Syke) spatial datasets for the current situation of the catchments in terms of drainage development. Pyhäntä gauging station has an upstream catchment area of 539 km^2 and is located between 28˚10′ and 29˚ East and 64°19′ to 64°30′ North. This catchment is one of the headwaters of the Oulujoki watershed and the station is based on the Hyrynsalmen Reitin Alaosa watercourse. In the northern part of Finland, the other catchment is Ounasjärvi-luusua, which is extended around 363 km^2, located between 23˚15′ and 23˚45′East and 68°16′ to 68°35′ North. Ounasjärvi-luusua is one of the most upstream catchments of Kemijoki and its outlet gauging station is located on the Ylä-Ounasjoen Alue watercourse (Fig. 1). Based on the Corine Land Cover (CLC) 2018 (Version 2020_20u1), the main land cover of both catchments is forest and wetlands. In addition, according to the topographic database of the National Land Survey of Finland, the drainage density (open ditches with 2–5-meter width (group 19, class 36311)), Pyhäntä catchment has been covered by a dense ditch network with the density of 9 km km^{-2} which is far more intensive than in Ounasjärvi-luusua with 0.7 km km^{-2}. This has been one of the main criteria for selecting these two catchments. Both catchments have subarctic climate, based on Köppen climate classification, including long cold winters and short cool summers. The long-term annual mean temperature in Pyhäntä is 1.5˚C ranging between -11.4 and 15.5 ˚C in January and July, respectively. Ounasjärvi-luusua, however is 3.3˚C colder with -1.8˚C long-term annual mean temperature ranging from -14.7˚C in January to 13˚C in July. On the other hand, Pyhäntä receives 664 mm of annual precipitation on a long-term average, 212 mm more than Ounasjärvi-luusua (452 mm). Based on the long-term records from the gauging stations, the discharge in Pyhäntä ranges from 0 to 100 m^3 s^{-1} and in Ounasjärvi-luusua between 0.3 to 66 m^3 s^{-1} (Table 1). The very low (0 and 0.3 m^3 s^{-1}) discharge usually happens in winter due to the freezing of the river, and the highest flow is in May due to the snow melt.

Data sources and preparation

In order to conduct the frequency analysis, the long-term annual and monthly maximums are extracted from the daily flow and precipitation datasets for the period 1961 to 2021. This period is selected due to limitations in the available historical daily climatology data, which is available from 1961 in the Finnish Meteorological Institute (FMI) ClimGrid dataset (described in (Aalto *et al.* 2016)). This dataset includes gridded daily climatology data with a spatial resolution of 10×10 km in Netcdf format. The historical time series of river flow is also acquired from the national environmental information database HERTTA. This data is available in daily time steps. Other spatial datasets used in this study are obtained from the Syke's spatial datasets. In order to consider the intensive development of drainage networks in Finland from the early 60s (Peltomaa 2007) (as a possible source of non-stationarity other than climatic variations), the annual and monthly maximums of precipitation and flow are split into two periods of almost the same size, 1961-1990 (30 years) and 1991–2021 (31 years) which from now on are called P-I and P-II respectively.

Generalized extreme value distribution (GEV)

Many combinations of different distributions are introduced for the best predictive fit to extremes time series, such as Gumble, Log-normal, Pearson type 3, Log Pearson type 3, Generalized extreme value, Generalized logistic, and etc (Bezak *et al.* 2014; Kobierska *et al.* 2018). However, there is no prior distribution and estimation method as they can be case-based and their performance varies in different climates and regions. Therefore, the selection of the most suitable distribution is always challenging and requires more extensive studies. In this study, we used stationary Generalized extreme value (GEV) (Coles 2001) since it showed better performance in the Nordic climate (Kobierska *et al.* 2018) and is widely accepted and suggested by many studies (Drissia *et al.* 2019; Haddad & Rahman 2008; Kyselý *et al.* 2007; Saf 2010; Ul Hassan *et al.* 2019). The GEV distribution is developed based on the Extreme Values theory (Haan & Ana 2006), combining the Gumbel, Fréchet and Weibull distribution families into one single distribution. The GEV is characterized by three parameters, a shape parameter (μ), location parameter (μ) and scale parameter (σ) (Equation (1)), which satisfy $\{x\text{: } 1+ \xi(x - \mu) / \sigma > 0 \}$, $-\infty < \mu < \infty$, $\sigma > 0$, and $-\infty < \xi < \infty$. The $\xi > 0$, $\xi < 0$, and $\xi = 0$ correspond to Fréchet, Weibull and Gumbel family distributions, respectively. The cumulative distribution and the return level estimator functions are presented in Eqs. (1) and (2):

$$F(x;\mu,\sigma,\xi) = \left\{ \begin{array}{l} \exp\left\{ \begin{array}{l} -\left(1+\dfrac{\xi(x-\mu)}{\sigma}\right)^{-\frac{1}{\xi}}, \\ 1+\dfrac{\xi(x-\mu)}{\sigma} > 0, \end{array} \right\} \xi \neq 0 \\ \exp\left\{ -\exp\left\{ -\dfrac{x-\mu}{\sigma} \right\} \right\}, \xi = 0 \end{array} \right\} \quad (1)$$

$$z_{\mathrm{p}} = \left\{ \begin{array}{ll} \mu - \dfrac{\sigma}{\xi}\left[1-\{-\log(1-p)\}^{-\xi}\right], & \text{for } \xi \neq 0 \\ \mu - \sigma \log\{-\log(1-p)\}, & \text{for } \xi = 0 \end{array} \right\}, (2)$$

where x is the annual maximum, p is the exceedance probability (return period = 1 / p), and $F(z_{\mathrm{p}})$ = 1 – p. This means that considering a reasonable degree of accuracy, it is expected that the return level z_{p} is exceeded every 1 / p years averagely. All the calculations, including the Netcdf data opening, annual and monthly-annual maximum extraction, and GEV method, were programmed in MATLAB. For fitting the GEV and extracting the return levels, the gevfit(x,α) and gevinv(p, ξ, σ, μ) functions were used where

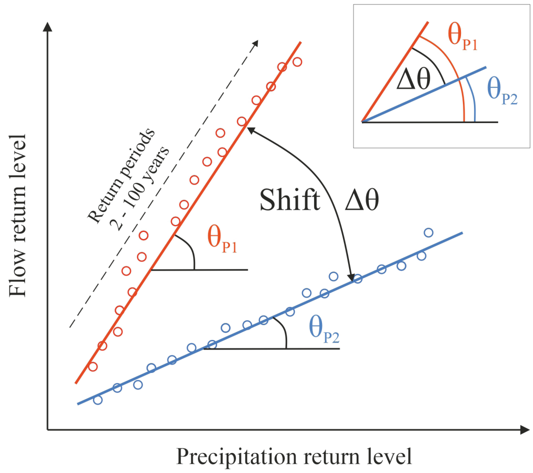

Fig. 2. The precipitation-flow return levels relationship and the θ index, illustrating their shifts in different periods.

100(1 – alpha)% is the confidence interval for the estimated parameters. Matlab uses Maximum Likelihood (ML) as the parameter estimator in gevfit.

Flow-Precipitation return levels relationship

To assess the possible shifts in the precipitation-flow return levels (RLs) relationship in different periods, a new index called Theta (θ) is defined, which is the slope of the linear relationship between precipitation-flow RLs (Fig. 2). Similar approach was used in (Saft *et al.* 2016) to evaluate interdecadal shifts in linear rainfall-runoff relationship. In real cases, the flood and storm frequencies of annual extremes can be noncorrelated due to numerous factors such as the climatological condition of the catchment, climate mode (El Niño-Southern Oscillation (ENSO) and the Pacific Oscillation (IPO)), catchment wetness, and etc (Sivapalan *et al.* 2005; Webster 2000). However, as the river flow is more sensitive to precipitation alteration in dry catchments, especially in sub-daily time scale (Wilusz *et al.* 2017), it is worthy to investigate if significant alterations are observed in wet cases in cold climate snow-dominant catchments. Similar to (Vangelis *et al.* 2022) and (Breinl *et al.* 2021), which aimed to compare different

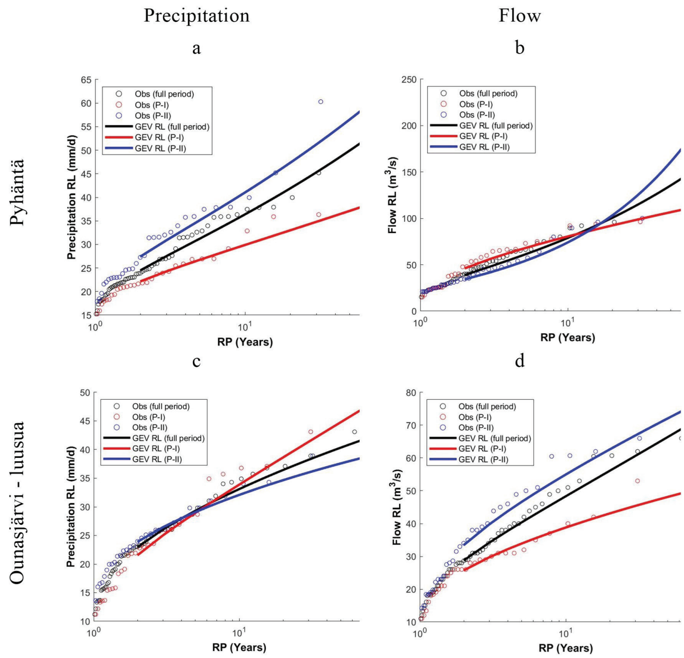

Fig. 3. The precipitation (**a**, **c**) and flow (**b**, **d**) frequencies for Pyhäntä (top) and Ounasjärvi-luusua (bottom) watersheds in two periods of 30 years, 1961 to 1990 (P-I) and 1991 to 2021 (P-II).

distribution models, here we aim to propose this approach to compare the return periods of different periods based on annual and monthly extremes and if this relationship has changed in different periods.

Results

Frequency analysis of annual extremes

The flow and precipitation return levels (RL) for the return periods (RP) of 2 to 100 for annual maximums were estimated for the two periods of 30 years, 1961 to 1990 (Period I (P-I)) and 1991 to 2021 (Period II (P-II)) (Fig. 3). At Pyhäntä station, precipitation extremes increase from 22.2 (RP 2 yrs) to 40.3 (RP 100 yrs) mm d^{-1} for P-I and from 27.4 (RP 2yrs) to 64.31 (RP 100 yrs) mm d^{-1} for P-II (Fig. 3a). In Ounasjärvi-luusua station, by increasing the RP from 2 to 100 years, the extreme precipitation rises from 21.5 (RP 2yrs) to 49.6 (RP 100yrs) mm d^{-1} and for P-I and 23.9 (RP 2yrs) to 39.5 (RP 100yrs) mm d^{-1} for P-II (Fig. 3c). The results show that the precipitation RLs are higher in P-II than in P-I in Pyhäntä station, increased between 23.8 and 59.5 percent (Fig. 3a), while at Ounasjärvi station, only the RPs of 2 to 5 years exhibited a higher frequency of up to 11% in P-II than in the P-I (Fig. 3c). The results for extreme flows are presented in Fig. 3b and 3d. These results show that for both periods in Pyhäntä, the flow RLs of the RPs increase from 46 to 116.8 m^3 s^{-1} (in P-I) and from 34.2 to 227.5 m^3 s^{-1} (in P-II) (Fig. 3b). Similarly, in Ounasjärvi-luusua, the flow RLs increase from 25.7 to 51.6 m^3 s^{-1} in P-I and from 33.5 to 78.9 m^3 s^{-1} (in P-II) for the RPs of 2 and 100 years respectively (Fig. 3d). Comparing the two periods in Pyhäntä, the severity of the floods with RPs of 2 to 13 years are predicted to be more in P-I based on the annual maximums. On the other hand, by increasing the RPs from 13 to 100 years, the RLs become higher in P-II within a range of 2.6 to 94.8% more than P-I (Fig. 3b). Similar comparison for Ounasjärvi-luusua shows that the extreme flows for all RPs are higher in P-II than P-I by an average of 48% (22.8 m^3 s^{-1}) over all RPs (Fig. 3d).

Monthly extreme frequency

Here, an overview of monthly extreme frequencies presented in Fig. 4 shows that most of the extreme flows, snow depth, precipitation,

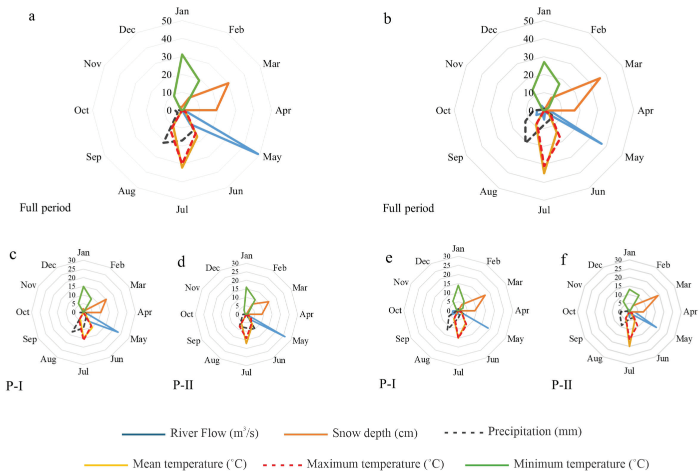

Fig. 4. The monthly frequency of annual extremes for Pyhäntä (**a**, **c**, **d**) and Ounasjärvi-luusua (**b**, **e**, **f**) watersheds in the whole two periods of 30 years, 1961 to 1990 (P-I) and 1991 to 2021 (P-II).

maximum temperature, minimum temperature, and mean temperature occurred in May, March, August, July, January, and July, respectively, in both watersheds. The large number of annual extreme flows occurring in May are clearly attributed to snow depth declining from April. Most of the annual extreme precipitations happen in July–September. Regarding the number of flow and precipitation extreme events, in Ounasjärvi-luusua, the extreme flow (precipitation) happened 49 (21) times in May (August) over the whole period of 61 years (Fig. 4a). Similarly, Pyhäntä experienced 37 (21) times of extreme flows (precipitation) in May (August) over the entire period (Fig. 4b). The results also show that the monthly scatter of extremes does not significantly change over the two periods P-I (Figs. 4c and 4e) and P-II (Figs. 4d and 4f) and the only obvious change is observed in precipitation extremes in Ounasjärvi-luusua where the extreme frequency shifted to June from P-I (Fig. 4c) to P-II (Fig. 4d). Overall, these results indicate that to assess the rainfall-dominated flows, autumn and winter flows should be considered (Matti *et al.* 2017c). Therefore, in the next sections, only the results of frequency analysis of monthly extremes are presented.

Frequency analysis of monthly extremes

The flow and precipitation RLs based on monthly maximums of full, P-I, and P-II periods in July, August, and September are presented in Figs. 5 and 6 for Pyhäntä and Ounasjärvi-luusua stations, respectively. The precipitation RLs of the full period in Pyhäntä catchment (Fig. 5a–c) range from 15.4 mm d^{-1} (RP = 2 years) in July to 47.8 mm d^{-1} (RP = 100 years) in September. The highest precipitation RL belongs to September (RP = 100 years) by 63.4 mm d^{-1} for P-II, and the lowest precipitation RLs in July (RP = 2 years) by 12.3 mm d^{-1} for P-I extremes. The precipitation RLs of different periods ranged from almost 0 to 35.1 mm d^{-1} in August and September accordingly. It is also shown in Fig. 5a-c that the RLs of P-II become higher than the full period and P-I following the incremental increase in RPs. The flow RLs of the full period (Fig. 5d–f) range between 9.9 m^3 s^{-1} (RP = 2 years) to 57.1 m^3 s^{-1} (RP = 100 years), which happened in July and September respectively. Comparing the two P-I and P-II periods, the results show that the highest and lowest flow RLs both belong to P-I extremes by 70.7 m^3 s^{-1} (RP = 100 years) and 8.1 m^3 s^{-1} (RP = 2 years) in September and July, respectively.

The results of Ounasjärvi-luusua station (Fig. 6) show that the precipitation RLs (Fig. 6a–c) of the full period range from 10.7 mm d^{-1} (RP = 2 years) in September to 49.6 mm d^{-1} (RP = 100 years) in August. Comparing the P-I and P-II periods, both the highest and lowest RLs occurred in period P-I by 55.9 mm d^{-1} in August (RP = 100 years) and 10.2 mm d^{-1} in September (RP = 2 years). Overall three months, the difference between the precipitation RLs of different periods varies between

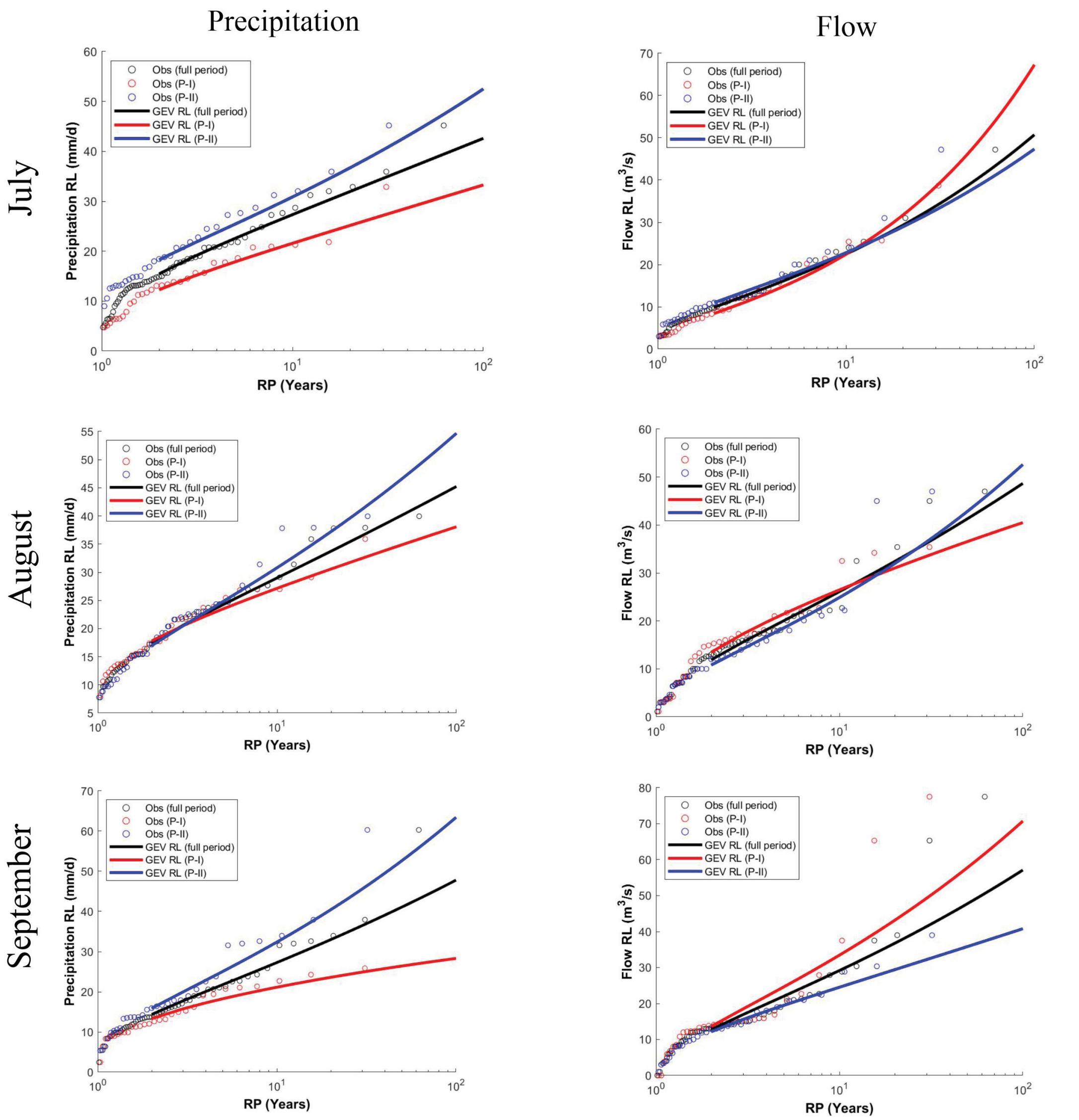

Fig. 5. The frequency analysis of monthly precipitation and flow extremes for Pyhäntä watershed in two periods of 30 years, 1961 to 1990 (P-I) and 1991 to 2021 (P-II).

0.1 and 9.3 mm d^{-1} in July and September in order. As presented in Fig. 6a-c, these differences increase in higher RPs. Following the increment in RPs, the RLs of P-II are higher than the full period and P-I in September, unlike July and August, in which the RLs of P-I are higher than the full period and P-II. Regarding the flow extremes (Fig. 6d–f), the RLs of the full period range between 4.8 m^3 s^{-1} (RP = 2 years) to 32.9 m^3 s^{-1} (RP = 100 years), which both happened in August. By splitting the annual extreme flows into P-I and P-II periods, the results show that the highest and lowest RLs belong to P-I and happened in August by 45.9 m^3 s^{-1} (RP = 100 years) and 4.22 m^3 s^{-1} (RP = 2 years) respectively. Figure 6d–f also shows that the difference between the precipitation RLs of different periods range from 0.03 and 17.1 m^3 s^{-1} both of which occurred in August. Moreover, the RLs of P-II for all RPs are higher than P-II and full period in all months except August, where the marginal differences happened. In the August case, the resulted RLs of 2 to 5 years are slightly higher in P-II than P-I in the other months; however, the RLs of P-I pass P-II after the RP of 6 years (Fig. 6e).

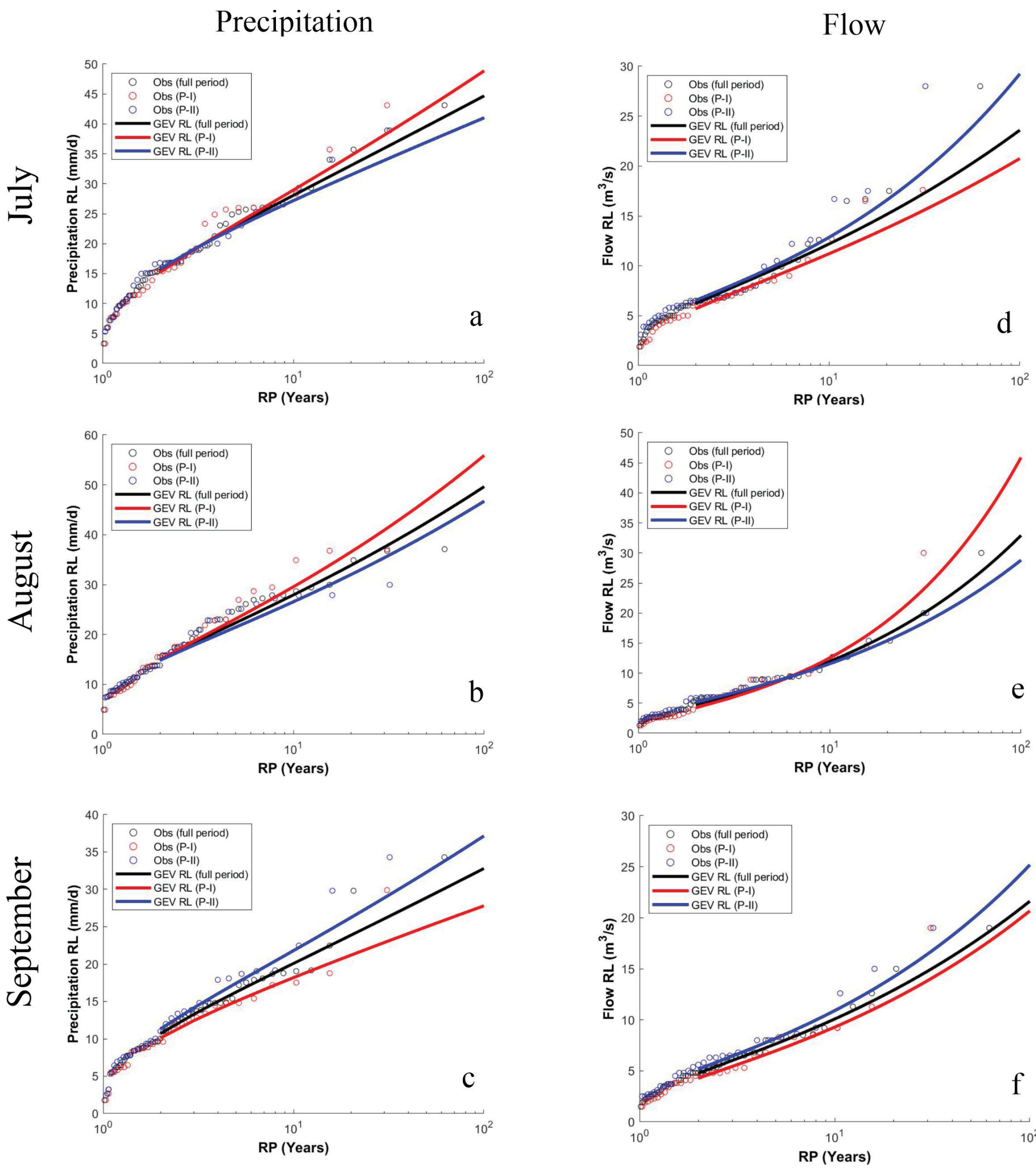

Fig. 6. The frequency analysis of monthly precipitation (left) and flow (right panels) extremes for Ounasjärvi-luusua watershed in two periods of 30 years, 1961 to 1990 (P-I) and 1991 to 2021 (P-II).

Watershed precipitation-flow extreme ratio

The linear relationship between precipitation and flow RLs based on annual (Fig. 7) and monthly (Fig. 8) maximums in P-I and P-II periods were estimated for Pyhäntä (Fig. 7 and Fig. 8a–c) and Ounasjärvi-luusua (Fig. 7 and Fig. 8d–f) catchments. Over the RLs of annual maximums, the θ index of P-I and P-II periods in Pyhäntä catchment is estimated to be 74.6° and 80.5° respectively, showing a difference ($\Delta\theta$) of 5.9° between the two periods (Fig. 7a). Similar to Pyhäntä catchment, θ in Ounasjärvi-luusua is higher in P-II (71.9°) than in P-I (40.8°) by a difference of 31.1° (Fig. 7b). In the monthly maximums case, the difference between the θ index of P-I and P-II periods in Pyhäntä catchment is –25.4° (Fig. 8a), –3.8° (Fig. 8b), and –48.5° (Fig. 8c) for the linear lines models of July, August, and September respec-

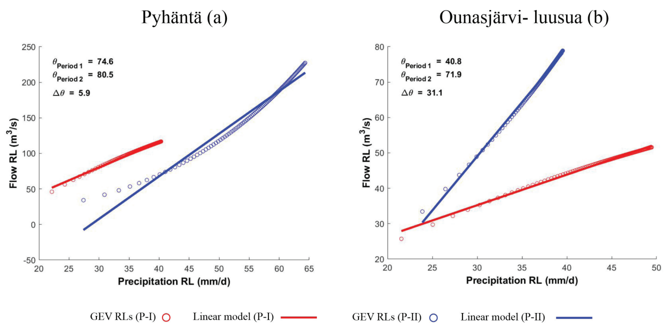

Fig. 7. The linear relationship and θ variation between precipitation and flow return levels for Pyhäntä (**a**) and Ounasjärvi-luusua (**b**) watersheds of annual extremes of P-I (1961 to 1990, blue line and markers) and P-II (1991 to 2021, red line and markers).

tively. This means that in Pyhäntä catchment, the θ index of P-I is higher than P-II and higher flow RLs are explained by the same precipitation RLs in the P-I period than in P-II. Similar negative $\Delta\theta$ are observed in the Ounasjärvi-luusua catchment in August and September by –10.2° (Fig. 8e) and –5.9° (Fig. 8f) as well, while $\Delta\theta$ is positive in July by 21.3° (Fig. 8d).

Discussion

Frequency alteration in annual extremes

The frequency analysis of annual precipitation extremes in the Pyhäntä catchment shows that the return levels increased by an average of 50% in the second period following the 21.1% increase in the observed extremes (see Fig. S1a in Supplementary Information). This increase can be explained by the almost 20% increase in the average annual precipitation and 27.8% increase in the magnitude of average annual extreme precipitation (Table 2). On the other hand, the flow frequency analysis in this station shows that the magnitude of flow return levels decreased by an average of 14% for the return periods of below 14 years but increased for higher return levels by an average of 55% (see Fig. S1a in Supplementary Information). Almost 93% of the observed flow extremes in Pyhäntä stations have a return period of below 14 years, decreased by an average of 8%, which explains the return level decline and also the 12.8% decrease in the average of annual extreme flow (Table 2). For Ounasjärvi-luusua annual extremes, the precipitation return levels and observed extremes of below 5 years return periods increased by an average of 5 and 15.1%, respectively, while for higher return periods, decreased by 15.1% and 9.3% (see Figs. 4a and S1b in Supplementary Information). This shows that the increase of 10.7% in the long-term annual average and 6% in the average of annual extreme in Ounasjärvi-luusua mainly impacted less rare precipitation events. This could be the main reason why only the return period of the events smaller than five years exhibits an increase in the second period (Table 2). The results also indicate that the flow return levels (see Fig. S1b in Supplementary Information) and observed extremes (Fig. 4d) increased by an average of 48.5% and 9.7%, respectively, which is attributed to the increase in the long-term annual average and the average of annual extremes by 20.2% and 33.7% respectively. The frequency analysis of annual extremes also shows that the changes in the observed flow extremes and estimated return levels are not clearly attributed to the precipitation extremes as the variation pattern of the return levels and observed extremes of different periods are different for flow and precipitation in both stations (Fig. 3). For example, in Pyhäntä, the precipitation extremes and return levels are higher in the second period while sequences of the periods are different for the flow extremes in which the return levels and observed extremes are higher in first period for the return periods of below 14 years but lower in the return periods of above 14 years (see Fig. S1a in Supplementary Information).

Frequency alteration in monthly extremes

The unique seasonality of the hydrologic and climatic extreme (Figs. 4a and b) could be a reason

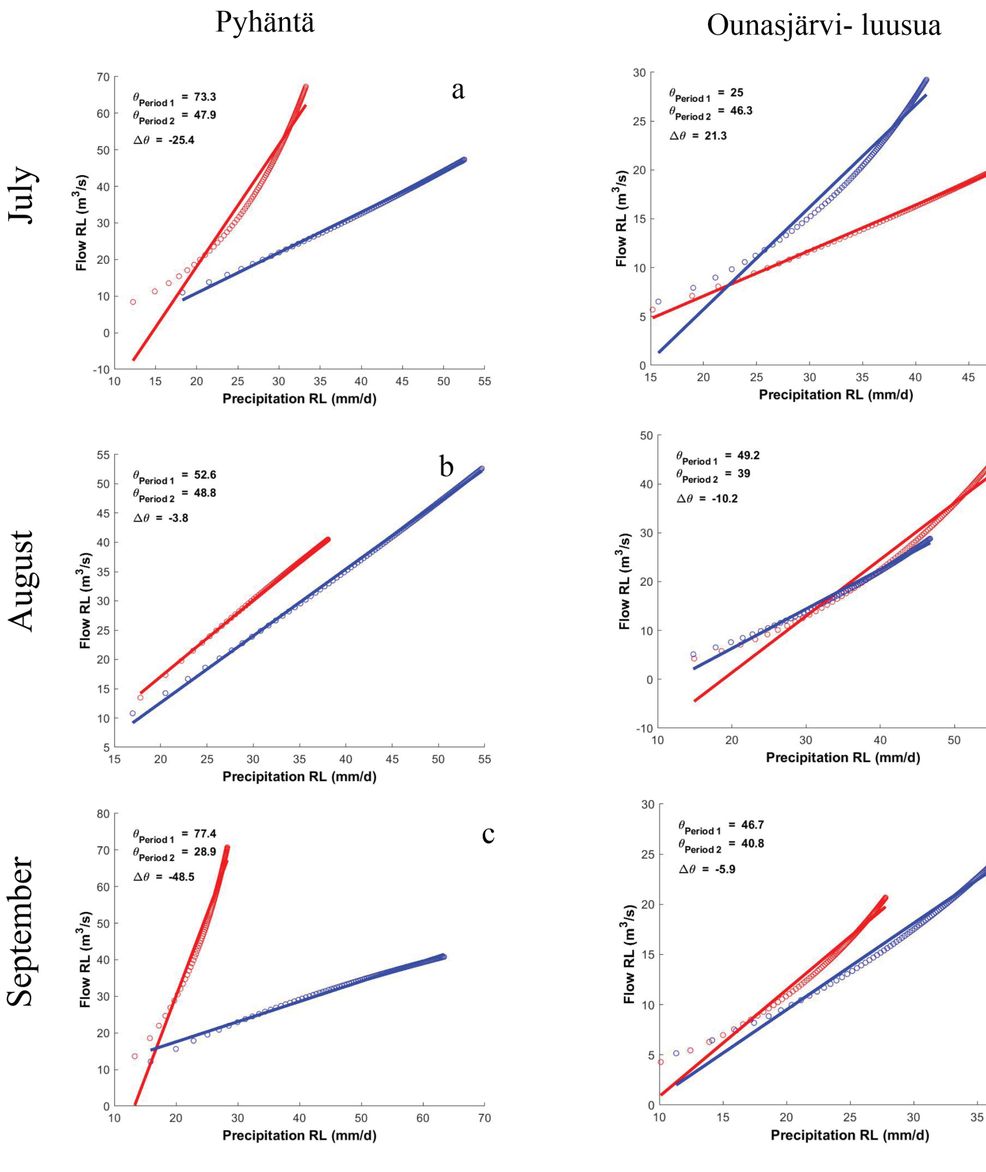

Fig. 8. The linear relationship and θ variation between precipitation and flow return levels for Pyhäntä (**a**–**c**) and Ounasjärvi-luusua (**d**–**f**) watersheds of monthly extremes of P-I (1961 to 1990, blue line and markers) and P-II (1991 to 2021, red line and markers).

for the lack of a clear relationship between annual precipitation and flow extremes. The substantial impact of temperature increase (see Fig. S2 in Supplementary Information) and the consequent faster snow melt in the snow melt season (April and May) highly impact the annual extremes frequency and magnitude. Frequency analysis for monthly maximums of the Pyhäntä catchment shows that during the precipitation dominant months (July-September), the precipitation return levels increased in the second period (Fig. 5a–c) following an increase in the frequency of observed extremes. In the other catchment, Ounasjärvi-luusua experienced different alterations in precipitation return levels compared to Pyhäntä, which decreased in the second period for July and August (Fig. 6a–c) and only increased in September. The flow return levels of monthly maximums (Fig. 5d–f) are not clearly attributed to the increases in precipitation return levels, although the observed flow extremes increased for all return periods in July and high return periods (> 10 years) in August. On the other hand, the flow return levels of September decreased in the second period despite the increase in precipitation return levels. According to the return levels and observed extreme variation (Fig. 5d–f), the differences between the two periods seem to be highly sensitive to large extremes, especially if the differences are low in low return periods (> 10 years). Here, the large extremes (highest return periods), which their magnitudes are significantly higher than the more frequent extremes, play a significant role in return level estimation by increasing the uncertainties. Example events can be given like the first and second highest extremes (31 and 16 years return period in order) in August with 47 (2004) and 45 (2012) $m^3 s^{-1}$ magnitude, respectively, which were the only events in the second period with higher magnitude than in the first period (34.2 (1971) and 32.5 (1961) $m^3 s^{-1}$) (Fig. 5e). Similar condition is observed in September in which the very large extreme flows of 6 to 31 years return periods (37.5, 65.3, 74, and 77.5 $m^3 s^{-1}$) in the second period posed the big differences with the extremes in the first period (21, 22.4, 28.9, 30.4, and 39 $m^3 s^{-1}$) (Fig. 5f).

In the other station, Ounasjärvi-luusua, the observed flow extremes averagely changed for 1.4, 0.3, and 1 $m^3 s^{-1}$ in the second period for July, August, and September extremes, respectively, overall return periods (1 to 31 years). The flow return level changes were different from the precipitation return levels only in July (Fig. 6d), while both flow and precipitation return levels in August (decreasing) (Fig. 6e) and September (increasing) (Fig. 6f) changed similarly in the second period. However, the magnitude of these changes is not large as their average for observed precipitation extremes are 0.2, 0.3, and 2 mm d^{-1}, and for flow 1.4, 0.3, and 1 $m^3 s^{-1}$ in July, August, and September, respectively. Such periodic variation in the frequency of extreme events, as well as the obscure relation of historical flows and precipitation events, require to be investigated by more comprehensive and systematic approaches like hydrological modeling. This will help to address the main factors involved in such variations. Many factors can be listed for the lack of hydrological response to the climatic variations like physical catchment characteristics, hydrologic seasonality, landcover change, and anthropogenic activities (C. Teutschbein, T. Grabs, R. H. Karlsen, H. Laudon 2015; Schelker *et al.* 2013; Zhang *et al.* 2017). For example, lakes can play a regulative role (like reservoirs) and capture extreme flows so that the impact of extreme precipitation is less observed in the catchment outlets. Moreover, forest cover naturally decreases the sensitivity of the flows to precipitation by acting as a natural buffer and absorbing excess precipitation. For example, in this study, considering the climate type of the catchments (cold region) and their main land cover (dense forest), the lack of relationship between precipitation and flow extremes and return levels can be due to the high snow melt discharge in spring and increased forest canopy interception in summer which plays a retaining role against precipitation.

Comparison between the two catchments

The different periodic changes of precipitation frequencies between the two catchments (Figs. 5 and 6) can be due to their different climatic conditions. The increase in all return periods of precipitation extremes in Pyhäntä and the decrease in these values only in high return periods in Ounasjärvi- unusual can possibly be impacted by regional climate variability. This needs to be investigated using regional climate analysis and evaluating different climate indices. Regarding the flows, the reasons behind the shifts in extremes and return levels from one period to another are different for the two catchments. In Ounasjärvi-luusua station, these shifts seem to be more uniform and impacted by climate variations like the collective impact of increased snow depth in winter (January–April) by 3.6% and increased average temperature in spring (April–June) by 19.4%. In Pyhäntä, many other factors, such as catchment characteristics, land cover change, and human activities, might contribute. In forested catchment cases like in this study, it is suggested that the return period could increase by the impact of forest harvesting and related management practices (drainage systems). Similar increases in the second period were expected for Pyhäntä as this catchment has been under drainage since the mid-first period. However, these impacts are not clearly observed in the results of this study, and the return levels showed more sensitivity to large, rare events.

Theta θ variation

The highest values of θ at the beginning of spring in Pyhäntä (April and May (Fig. 9a)) and Ounasjärvi-luusua (May and June (Fig. 9b)) show that these values are more impacted by snow melt-induced return levels. Moreover, the proximity of θ values in these months to the annual values shows that these months contribute more to the annual values than the other months. This observation also confirms the high impact of snowmelt on annual extreme levels. In some other months, the θ values are close to the annual ones as well, such as the θs in the first period for September, October, and December in Pyhäntä. For example, the θ in September for the return levels of the first period is estimated to be higher than the second period with a large margin (48.5°). This probably happened due to the very large events that occurred in the first period of this month, like 77.5 (in 1962), 74 (in 1983), and 65.3 (in 1967) $m^3 s^{-1}$ for the return periods of 31, 15, and 10 years. These events were 49.7%, 59%, and 55.9% higher than the floods with the same return periods in the second period which consequently impacted the estimated return levels. From physical insight, Shifts in θ between different periods and/or catchments are expected due to the varied climatological and hydrological characteristics of the catchments. These include differences in precipitation regimes, antecedent soil moisture, evapotranspiration, and runoff generation efficiency. The variability in $\Delta\theta$ across summer months in Fig. 8 likely reflects such non-uniform seasonal shifts between the two periods. For instance, in Ounasjärvi (d), July shows a positive $\Delta\theta$, indicating a steeper precipitation–flow return level relationship in the later period (P-II). This may result from more frequent or intense precipitation events during July in P-II in Ounasjärvi-luusua, coupled with wetter later conditions, enhancing runoff. In contrast, August and September (e and f) show negative $\Delta\theta$, possibly due to smaller changes in precipitation characteristics or already saturated catchments, leading to a reduced marginal response of flow to precipitation.

Uncertainties

Estimating return levels in flood frequency analysis are subject to various sources of uncertainty like inadequate data records, data errors (in collection, recording, or entry), different sources of non-stationarity, and distribution parameters estimation. One source can be the utilization of gridded data (Arheimer & Lindström 2015), which might have failed to capture local extreme precipitation. Most of the uncertainties in short-length data records arise from large, rare events compared to normal floods (Yan *et al.* 2021). Such events impact the parameter estimation for extreme value distributions. The parameter estimation can be particularly prone to bias when there are only a few data points in the tail of the distribution, pulling the tail in the direction of the outliers. This can result in wider confidence intervals and less reliable predictions of extreme events (see Figs. S3 and S4 in Supplementary Information), especially for the return periods higher than the length of the data (e.g., 100-year return period). Such uncertainties are intensified when shorter periods are considered and include those large events. For instance, the largest flood in Pyhäntä station over the entire period of records (61 years) is 100 $m^3 s^{-1}$ with the return period of 62 years (1.6% exceedance probability) (see Fig. S3a in Supplementary Information), while the return period of this event decreases to 31-years (becomes more likely with 3% exceedance probability) when the data records are split to two periods (see Fig. S3c in Supplementary Information). Similarly, the return period for this event could be possibly higher in longer data length (> 61 years). To reduce the uncertainties

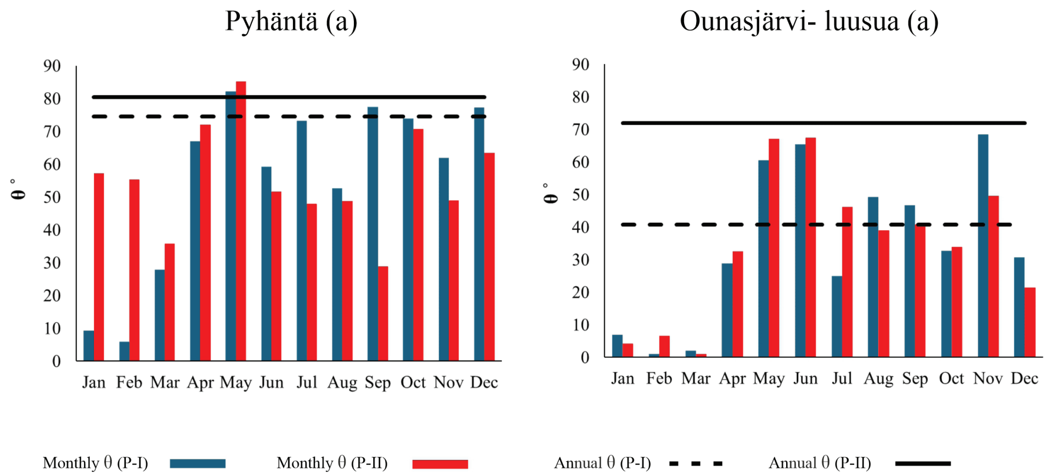

Fig. 9. The monthly variation of θ index in two periods of 1961–1990 and 1991–2021 for (**a**) Pyhäntä and (**b**) Ounasjärvi-luusua stations.

associated with the short length data, the use of a regional frequency analysis is recommended. Moreover, the accuracy of the estimated return levels and confidence intervals are influenced by the parameter estimator as well and testing different estimators are recommended.

Conclusion

Nordic climate is characterized by snow and rainfall-dominated seasons, uniquely influencing river regimes in Nordic watersheds. Moreover, this region's unique landscape consists of lakes and different forest covers. Over the past decades, these distinct characteristics, combined with climate variability and extended human activities, have affected the frequency and intensity of extreme events in this region. This study focused on evaluating the frequency alteration of precipitation and flow extremes between two periods of 30 years in two catchments with different characteristics in Finland. The results show that the hydrological and meteorological time series are varied, affected by the non-stationarities arising from climate variability, increased annual average temperature, and the development and maintenance of drainage systems. The frequency behaviors from one period to another were different in the two catchments. The impact of climatic variability is also different in the two catchments, where the increased annual temperature and precipitation increased the precipitation frequencies of all return periods. In the other, it only impacted the less rare events. Moreover, the annual flow frequencies are ruled by snow melt rather than the precipitation; even the summer extremes can be still impacted by spring extremes (snow melt induced flows). The results also showed that compared to normal extremes, rare large events in any period of assessment can significantly alter the frequency estimations and increase the associated uncertainties. The combination of such events with the remaining flows from spring snow melt could disturbed the association of precipitation and flow frequencies. These findings highlight the complexity of extreme event behavior in Nordic catchments, as well as the limitations of analyzing changes using stationary methods over limited observation periods. Given the observed spatial and temporal variability, particularly in response to climatic and hydrological factors, further studies incorporating seasonal, regional, and nonstationary frequency analyses are warranted to improve the understanding and prediction of extreme events in similar environments.

Acknowledgements: The first author acknowledges the Arctic Interactions research profile action of the University of Oulu, Riitta ja Jorma J. Takasen, and OLVI foundations for their generous supports. The ArcI (Arctic Interactions profi 4) funding by the Academy of Finland supported the corresponding author's doctoral research and studies including the current article.

References

Aalto, J., Pirinen, P., & Jylhä, K. (2016). New gridded daily climatology of Finland: Permutation-baseduncertainty estimates and temporal trends in climate. *Journal of Geophysical Research: Atmospheres*, *121*(8), 3807–3823. https://doi.org/10.1002/2015JD024651

Albrecht, E. (2023). Changing Winters and Adaptive Water Governance: A Case Study on the Kemi River Basin, Finland. *Water (Switzerland)*, *15*(11). https://doi.org/10.3390/w15112024

Arheimer, B., & Lindström, G. (2015). Climate impact on floods: Changes in high flows in Sweden in the past and the future (1911-2100). *Hydrology and Earth System Sciences*, *19*(2), 771–784. https://doi.org/10.5194/hess-19-771-2015

Bezak, N., Brilly, M., & Šraj, M. (2014). Comparaison entre les méthodes de dépassement de seuil et du maximum annuel pour les analyses de fréquence des crues. *Hydrological Sciences Journal*, *59*(5), 959–977. https://doi.org/10.1080/02626667.2013.831174

Breinl, K., Lun, D., Müller-Thomy, H., & Blöschl, G. (2021). Understanding the relationship between rainfall and flood probabilities through combined intensity-duration-frequency analysis. *Journal of Hydrology*, *602*(March). https://doi.org/10.1016/j.jhydrol.2021.126759

Brunner, M. I., & Fischer, S. (2022). Snow-influenced floods are more strongly connected in space than purely rainfall-driven floods. *Environmental Research Letters*, *17*(10). https://doi.org/10.1088/1748-9326/ac948f

C. Teutschbein, T. Grabs, R. H. Karlsen, H. Laudon, and K. B. (2015). Hydrological response to changing climate conditions: Spatial streamflow variability in the boreal region. *Journal of the American Water Resources Association*, *51*, 9425–9446. https://doi.org/10.1111/j.1752-1688.1969.tb04897.x

Coles, S. (2001). An Introduction to Statistical Modeling of Extreme Values. In *Springer*. Springer London. https://doi.org/10.1007/978-1-4471-3675-0

Dahlke, H. E., Lyon, S. W., Stedinger, J. R., Rosqvist, G., & Jansson, P. (2012). Contrasting trends in floods for two sub-arctic catchments in northern Sweden - Does glacier presence matter? *Hydrology and Earth System Sciences*, *16*(7), 2123–2141. https://doi.org/10.5194/hess-16-2123-2012

Drissia, T. K., Jothiprakash, V., & Anitha, A. B. (2019). Flood Frequency Analysis Using L Moments: a Comparison between At-Site and Regional Approach. *Water Resources Management*, *33*(3), 1013–1037. https://doi.org/10.1007/s11269-018-2162-7

Dyrrdal, A. V., Saloranta, T., Skaugen, T., & Stranden, H. B. (2013). Changes in snow depth in Norway during the period 1961-2010. *Hydrology Research*, *44*(1), 169–179. https://doi.org/10.2166/nh.2012.064

Engeland, K., Aano, A., Steffensen, I., Støren, E., & Paasche, O. (2020). New flood frequency estimates for the largest river in Norway based on the combination of short and long time series. *Hydrology and Earth System Sciences*, *24*(11), 5595–5619. https://doi.org/10.5194/hess-24-5595-2020

Gohari, A., Jalali Shahrood, A., Ghadimi, S., Alborz, M., Patro, E. R., Klöve, B., & Torabi Haghighi, A. (2022a). A century of variations in extreme flow across Finnish rivers. *Environmental Research Letters*, *17*(12). https://doi.org/10.1088/1748-9326/aca554

Gohari, A., Jalali Shahrood, A., Ghadimi, S., Alborz, M., Patro, E. R., Klöve, B., & Torabi Haghighi, A. (2022b). A century of variations in extreme flow across Finnish rivers. *Environmental Research Letters*, *17*(12). https://doi.org/10.1088/1748-9326/aca554

Haan, L., & Ana, F. (2006). *Extreme Value Theory: An Introduction*. Springer. https://doi.org/https://doi.org/10.1007/0-387-34471-3

Haddad, K., & Rahman, A. (2008). Investigation on at-site Flood Frequency Analysis in South-East Australia. *Journal-The Institution of Engineers*, *69*(3).

Hailemariam, S. F., & Alfredsen, K. (2023). Quantitative Flood Risk Assessment in Drammenselva River, Norway. *Water (Switzerland)*, *15*(5). https://doi.org/10.3390/w15050920

Hisdal, H., Roald, L. A., & Beldring, S. (2006). Past and future changes in flood and drought in the Nordic countries. *IAHS-AISH Publication*, *308*, 502–507.

Instanes, A., Kokorev, V., Janowicz, R., Bruland, O., Sand, K., & Prowse, T. (2016). Changes to freshwater systems affecting Arctic infrastructure and natural resources. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 567–585. https://doi.org/10.1002/2015JG003125

IPCC. (2022). Climate Change 2022_ Impacts, Adaptation and Vulnerability_Working Group II contribution to the Sixth Assessment Report of the Intergovernamental Panel on Climate Change. In *Working Group II contribution to the Sixth Assessment Report of the Intergovernamental Panel on Climate Change* (Issue August).

Johnson, R. S. H., & Alila, Y. (2023). Nonstationary stochastic paired watershed approach: Investigating forest harvesting effects on floods in two large, nested, and snow-dominated watersheds in British Columbia, Canada. *Journal of Hydrology*, *625*(PA), 129970. https://doi.org/10.1016/j.jhydrol.2023.129970

Kobierska, F., Engeland, K., & Thorarinsdottir, T. (2018a). Evaluation of design flood estimates - a case study for Norway. *Hydrology Research*, *49*(2), 450–465. https://doi.org/10.2166/nh.2017.068

Kobierska, F., Engeland, K., & Thorarinsdottir, T. (2018b). Evaluation of design flood estimates - a case study for Norway. *Hydrology Research*, *49*(2), 450–465. https://doi.org/10.2166/nh.2017.068

Koskela, J. J., & Linjama, J. (2015). Design floods for small forested and agricultural catchments in Finland. *20th International Northern Research Basins Symposium and Workshop*, 33–34.

Kundzewicz, Z. (2019). Keeping Our Heads Above Water. *ACADEMIA-The Magazine of the Polish Academy ….* https://informacje.pan.pl/images/serwis/2019/academia-climate-change/kolumna/044-047_kundzewicz_ang.pdf

Kura, P. K., Alila, Y., & Weiler, M. (2012). Forest harvesting effects on the magnitude and frequency of peak flows can increase with return period. *Water Resources Research*, *48*(1), 1–19. https://doi.org/10.1029/2011WR010705

Kyselý, J., Picek, J., & Huth, R. (2007). Formation of homogeneous regions for regional frequency analysis of extreme precipitation events in the Czech Republic. *Studia Geophysica et Geodaetica*, *51*(2), 327–344. https://doi.org/10.1007/s11200-007-0018-3

Lawrence, D. (2020). Uncertainty introduced by flood frequency analysis in projections for changes in flood magnitudes under a future climate in Norway. *Journal of Hydrology: Regional Studies*, *28*(February), 100675. https://doi.org/10.1016/j.ejrh.2020.100675

Lawrence, D., Graham, L. P., den Besten, J., Andréasson, J., Bergström, S., Engen-Skaugen, T., Førland, E., Roen, R., Jespersen, M., de Jong, K., & Olsson, J. (2012). *Climate change impacts and uncertainties in flood risk management: Examples from the North Sea Region* (Vol. 1). Norwegian Water Resources and Energy Directorate. http://cardio.medi.ru/66_1205a.htm

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., & Kaspar, F. (2006). Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis. *Climatic Change*, *75*(3), 273–299. https://doi.org/10.1007/s10584-006-6338-4

Lintunen, K., Uvo, C. B., Alho, P., & Kasvi, E. (2023). *Hydrological variability of Finnish free-flowing rivers*. 12267.

Lundin, L. (1994). Impacts of forest drainage on flow regime. *Studia Forestalia Suecica*, *192*(192), 1–22.

Matti, B., Dahlke, H. E., Dieppois, B., Lawler, D. M., & Lyon, S. W. (2017a). Flood seasonality across Scandinavia—Evidence of a shifting hydrograph? *Hydrological Processes*, *31*(24), 4354–4370. https://doi.org/10.1002/hyp.11365

Matti, B., Dahlke, H. E., Dieppois, B., Lawler, D. M., & Lyon, S. W. (2017b). Flood seasonality across Scandinavia—Evidence of a shifting hydrograph? *Hydrological Processes*, *31*(24), 4354–4370. https://doi.org/10.1002/hyp.11365

Matti, B., Dahlke, H. E., Dieppois, B., Lawler, D. M., & Lyon, S. W. (2017c). Flood seasonality across Scandinavia—Evidence of a shifting hydrograph? *Hydrological Processes*, *31*(24), 4354–4370. https://doi.org/10.1002/hyp.11365

Matti, B., Dahlke, H. E., & Lyon, S. W. (2016). On the variability of cold region flooding. *Journal of Hydrology*, *534*, 669–679. https://doi.org/10.1016/j.jhydrol.2016.01.055

Osuch, M., Wawrzyniak, T., & Łepkowska, E. (2022). Changes in the flow regime of High Arctic catchments with different stages of glaciation, SW Spitsbergen. *Science of the Total Environment*, *817*. https://doi.org/10.1016/j.scitotenv.2022.152924

Peltomaa, R. (2007). Drainage of forests in Finland. *Irrigation and Drainage*, *56*(SUPPL. 1), 151–159. https://doi.org/10.1002/ird.334

Saf, B. (2010). Assessment of the effects of discordant sites on regional flood frequency analysis. *Journal of Hydrology*, *380*(3–4), 362–375. https://doi.org/10.1016/j.jhydrol.2009.11.011

Saft, M., Peel, M. C., Western, A. W., & Zhang, L. (2016). Predicting shifts in rainfall-runoff partitioning during multiyear drought: Roles of dry period and catchment characteristics. *Journal of the American Water Resources Association*, *52*, 9290–9305. https://doi.org/10.1002/2016WR019525

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K., & Laudon, H. (2013). Hydrological effects of clear-cutting in a boreal forest - Snowpack dynamics, snowmelt and streamflow responses. *Journal of Hydrology*, *484*, 105–114. https://doi.org/10.1016/j.jhydrol.2013.01.015

Schnorbus, M., & Alila, Y. (2013). Peak flow regime changes following forest harvesting in a snow-dominated basin : Effects of harvest area, elevation, and channel connectivity. *Water Resources Research*, *49*(1), 517–535. https://doi.org/10.1029/2012WR011901

Sivapalan, M., Blöschl, G., Merz, R., & Gutknecht, D. (2005). Linking flood frequency to long-term water balance: Incorporating effects of seasonality. *Water Resources Research*, *41*(6), 1–17. https://doi.org/10.1029/2004WR003439

Thorarinsdottir, T. L., Hellton, K. H., Steinbakk, G. H., Schlichting, L., & Engeland, K. (2018). Bayesian Regional Flood Frequency Analysis for Large Catchments. *Water Resources Research*, *54*(9), 6929–6947. https://doi.org/10.1029/2017WR022460

Ul Hassan, M., Hayat, O., & Noreen, Z. (2019a). Selecting the best probability distribution for at-site flood frequency analysis; a study of Torne River. *SN Applied Sciences*, *1*(12), 1–10. https://doi.org/10.1007/s42452-019-1584-z

Ul Hassan, M., Hayat, O., & Noreen, Z. (2019b). Selecting the best probability distribution for at-site flood frequency analysis; a study of Torne River. *SN Applied Sciences*, *1*(12), 1–10. https://doi.org/10.1007/s42452-019-1584-z

Vangelis, H., Zotou, I., Kourtis, I. M., Bellos, V., & Tsihrintzis, V. A. (2022). Relationship of Rainfall and Flood Return Periods through Hydrologic and Hydraulic Modeling. *Water (Switzerland)*, *14*(22). https://doi.org/10.3390/w14223618

Veijalainen, N. (2012). Estimation of climate change impacts on hydrology and floods in Finland. In *Aalto University*.

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B., & Käyhkö, J. (2010a). National scale assessment of climate change impacts on flooding in Finland. *Journal of Hydrology*, *391*(3–4), 333–350. https://doi.org/10.1016/j.jhydrol.2010.07.035

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B., & Käyhkö, J. (2010b). National scale assessment of climate change impacts on flooding in Finland. *Journal of Hydrology*, *391*(3–4), 333–350. https://doi.org/10.1016/j.jhydrol.2010.07.035

Veijalainen, N., & Vehviläinen, B. (2008). The effect of climate change on design floods of high hazard dams in Finland. *Hydrology Research*, *39*(5–6), 465–477. https://doi.org/10.2166/nh.2008.202

Vormoor, K., Lawrence, D., Schlichting, L., Wilson, D., & Wong, W. K. (2016). Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. *Journal of Hydrology*, *538*, 33–48. https://doi.org/10.1016/j.jhydrol.2016.03.066

Walsh, J. E., Ballinger, T. J., Euskirchen, E. S., Hanna, E., Mård, J., Overland, J. E., Tangen, H., & Vihma, T. (2020). Extreme weather and climate events in northern areas: A review. *Earth-Science Reviews*, *209*(August), 103324. https://doi.org/10.1016/j.earscirev.2020.103324

Webster, P. J. (2000). Factors affecting the relationship between the frequency of a flood and its causative rainfall. *AHS-AISH Publication*, 251–258.

Wei, X., Giles-Hansen, K., Spencer, S. A., Ge, X., Onuchin, A., Li, Q., Burenina, T., Ilintsev, A., & Hou, Y. (2022). Forest harvesting and hydrology in boreal Forests: Under an increased and cumulative disturbance context. *Forest Ecology and Management*, *522*(April), 120468. https://doi.org/10.1016/j.foreco.2022.120468

Wilson, D., Hisdal, H., & Lawrence, D. (2010). Has streamflow changed in the Nordic countries? - Recent trends and comparisons to hydrological projections. *Journal of Hydrology*, *394*(3–4), 334–346. https://doi.org/10.1016/j.jhydrol.2010.09.010

Wilusz, D. C., Harman, C. J., & Ball, W. P. (2017). Sensitivity of Catchment Transit Times to Rainfall Variability Under Present and Future Climates. *Water Resources Research*, *53*(12), 10231–10256. https://doi.org/10.1002/2017WR020894

Yan, L., Xiong, L., Ruan, G., Zhang, M., & Xu, C. Y. (2021). Design flood estimation with varying record lengths in Norway under stationarity and nonstationarity scenarios. *Hydrology Research*, *52*(6), 1596–1614. https://doi.org/10.2166/NH.2021.026

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y., & Liu, S. (2017). A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology*, *546*, 44–59. https://doi.org/10.1016/j.jhydrol.2016.12.040