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Flood seasonality across Scandinavia – Evidence of a shifting hydrograph?

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Abstract

Fluvial flood events have substantial impacts on humans, both socially and economically, as well as on ecosystems (e.g. hydroecology, pollutant transport). Concurrent with climate change the seasonality of flooding in cold environments is expected to shift from a snowmelt-dominated to a rainfall-dominated flow regime. This would have profound impacts on water management strategies, i.e. flood risk mitigation, drinking water supply and hydro power. In addition, cold climate hydrological systems exhibit complex interactions with catchment properties and large-scale climate fluctuations making the manifestation of changes difficult to detect and predict. Understanding a possible change in flood seasonality and defining related key drivers therefore is essential to mitigate risk and to keep management strategies viable under a changing climate.

This study explores changes in flood seasonality across near-natural catchments in Scandinavia using circular statistics and trend tests. Results indicate strong seasonality in flooding for snowmelt-dominated catchments with a single peak occurring in spring and early summer (March through June), whereas flood peaks are more equally distributed throughout the year for catchments located close to the Atlantic coast and in the south of the study area. Flood seasonality has changed over the past century seen as decreasing trends in summer maximum daily flows and increasing winter and spring maximum daily flows with 5-35% of the catchments showing significant changes at the 5% significance level. Seasonal mean daily flows corroborate those findings with higher percentages (5-60%) of the catchments showing statistically significant changes. Alterations in annual flood occurrence also point toward a shift in flow regime from snowmelt-dominated to rainfall-dominated with consistent changes toward earlier timing of the flood peak (significant for 25% of the catchments). Regionally consistent patterns suggest a first order climate control as well as a local second order catchment control which causes inter-seasonal variability in the streamflow response.

Key words: flood seasonality, Scandinavia, circular statistics, Mann Kendall test, trend analysis

Running head: Shifting flood seasonality across Scandinavia

1 Introduction

Flood seasonality is an important feature of the annual hydrograph characterizing the distribution of streamflow throughout the year. Characterizing the distribution of flow and thus flood seasonality is crucial not only for water management purposes such as hydro power and drinking water supply, but also flood management (Cunderlik et al., 2004; Barnett et al., 2005; Hannaford and Buys, 2012; Berghuijs et al., 2014; Engelhardt et al., 2014; Villarini, 2016). For much of the globe, annual temperature and precipitation are projected to increase due to climate change (IPCC, 2013). This is especially true in cold and temperate environments of the northern hemisphere (Screen, 2014; Donat et al., 2016). Further, extreme events are likely to occur more frequently (Alexander et al., 2006; Donat et al., 2013), which would affect streamflow in terms of both timing and magnitude (Wilby et al., 2008; Hannaford and Buys, 2012; Mallakpour and Villarini, 2015).

To this end and looking toward the future conditions, climate change impact studies have typically focused on flood seasonality to improve understanding of streamflow response under changing climate conditions and their drivers (Hannaford, 2015; Berghuijs et al., 2016). However, there has been limited consensus with regards to how climate and landscape changes manifest in the hydrological response as streamflow seasonality shifts. For example, variable trends with few catchments showing significance in streamflow signatures (e.g. mean flows, high flows) have been detected for northern Europe reflecting both methodological limitations and the complex interactions often found in cold climate systems (Wilson et al., 2010; Hall et al., 2014; Matti et al., 2016). Local factors such as geology, vegetation, soil properties and freeze-thaw patterns have been shown to have a profound influence on streamflow response, especially in cold regions such as northern Scandinavia where they can bring about variability in hydrological trends (Sjöberg et al., 2013; Fleming and Dahlke, 2014).

Despite such regional disparity owing to landscape controls and due to the close proximity to the Atlantic, Scandinavian streamflow is known to be affected by large-scale climate circulations over the Atlantic influencing both climate variables and streamflow (Busuioc et al., 2001; Dahlke et al., 2012). Especially in Norway, large-scale atmospheric circulation patterns (e.g. the North Atlantic Oscillation) have a profound influence on streamflow (Støren et al., 2012), where distinct regions have been determined using streamflow characteristics based on the annual hydrograph (Vormoor et al., 2015). Climate patterns are also known to cause variability in streamflow leading to non-stationarity and thus difficulties in determining historical trends as well as projecting streamflow into the future (Hall et al., 2014; Merz et al., 2014). This mixture of large-scale signals, non-stationarity, variability and local factors adds to the complexity of clearly characterizing patterns of current (and potential future) hydrological extremes across cold environments.

Streamflow across Scandinavia is typically snowmelt-dominated in the northern colder environments and rainfall-dominated in the more temperate south (Arheimer and Lindström, 2015; Mediero et al., 2015). Across northern Europe, streamflow changes during the last century point toward decreasing annual maximum daily streamflow for snowmelt-dominated catchments and an earlier occurrence of the flood peak caused by a decrease in snow cover during winter and higher winter temperature (Callaghan et al., 2010; Matti et al., 2016; Vormoor et al., 2016). At the same time, studies have shown that streamflow is likely to increase in autumn caused by rainfall floods which indicates a shift in flow regime from snowmelt-dominated to rainfall-dominated systems (Arheimer and Lindström, 2015; Vormoor et al., 2016). With climate change, snowmelt-dominated streamflow is expected to change, similar to what is observed for much of North America (Cunderlik and Ouarda, 2009; Burn et al., 2010; Fleming et al., 2016). Such shifts in flow regime would have profound impacts on water management strategies since a subsequent increase in mean annual streamflow is often expected (Berghuijs et al., 2014). Across much of Canada, for example, the development of an intermediate, bi-modal or mixed flow regime with a snowmelt peak in spring and a rainfall peak in autumn has been shown (Cunderlik and Ouarda, 2009). Traditionally, trend studies targeting characterization of changes in streamflow have been conducted on annual flows which bring about difficulties assessing such shifts in flow regime. This is especially true for snowmelt-dominated catchments where the spring peak is often about twice the magnitude of the autumn peak (Arheimer and Lindström, 2015). Furthermore, snowmelt-dominated regions have been explored for human induced changes, especially those causing non-stationarity in hydrological time series (Villarini, 2016). Non-stationarity in time series caused by climate or through direct anthropogenic impacts have been widely addressed as well as related limitations of current statistical models (Milly et al., 2008; Stedinger and Griffis, 2011; Vogel et al., 2011; Merz et al., 2014).

As such, there is a need for testing new techniques for assessing seasonality shifts especially in these snow-dominated regions where non-stationarity potentially is a central feature. To that end, circular statistics have been recognized as useful to explore flood seasonality and changes therein as they allow plotting annual data on a circle to visualize the data without gaps (Bayliss and Jones, 1993; Villarini, 2016; Blöschl et al., 2017). Circular statistics in combination with trend analysis may thus provide a powerful tool to assess changes in magnitude and timing of streamflow (flood seasonality) and changes therein allowing for using that deeper understanding for future projections.

From this perspective, this current study explores the potential for identifying changes in flood seasonality for near-natural catchments across Scandinavia using circular statistics and trend tests covering a range of temporal scales over the last century. We hypothesize that snowmelt-dominated catchments in Scandinavia show a shift in their annual hydrograph toward rainfall-dominated. This shift will be manifested through a decreasing snowmelt peak magnitude in spring coupled with an earlier occurrence of the snowmelt peak. At the same time, autumn and winter flows caused by rainfall events are expected to increase. Owing to system complexity and the importance of flood seasonality, further knowledge on changes in streamflow magnitude and timing in response to climate change is needed to be able to keep water management strategies viable under future conditions. Gaining a better understanding of Scandinavian flow regimes and changes therein in relation to climate change are thus crucial to meet those needs.

2 Methods

2.1 Study area and data

This study explores changes in flood seasonality across near-natural catchments in Scandinavia (specifically Sweden, Norway and Denmark). The catchments considered are characterized by having a minimum of 50 years of daily streamflow data and by not being influenced by regulation (i.e. dams or major flow control structures). Catchment areas range between 2 and 34,000 km^2 and cover elevations from sea level to 2,200 m a.s.l. The latitudes for the drainage area of each catchment range between 55 and 70° N. Over this region, the Scandinavian mountain range with elevations up to 2,500 m a.s.l. denotes the water divide between Norway and Sweden and determines whether a stream flows to the Baltic Sea in the east or the Atlantic Ocean in the west.

Scandinavian climate is characterized by a north-south gradient ranging from sub-arctic/alpine climate in the north and higher elevation areas to temperate climate in the south and along the Norwegian Atlantic coast which is mild and ocean influenced. Cold climate areas are characterized by winter precipitation falling as snow causing a snowmelt-dominated streamflow regime with a single pronounced peak in the annual hydrograph occurring in spring driven by snowmelt (i.e. the spring flood or freshet). Precipitation in the more temperate areas occurs mainly as late autumn and winter rainfall events leading to a rainfall-dominated streamflow regime with a peak discharge occurring during the wet season in (late) autumn and winter (Arheimer and Lindström, 2015; Mediero et al., 2015; Vormoor et al., 2015).

Mean annual temperature across Scandinavia ranges from -9 to +9°C with the lowest values occurring at higher elevations and latitudes. Mean annual precipitation is the highest along the west coast of Norway with values of up to 2,500 mm and characterized by a west-east gradient with the lowest values (400 mm) in northeastern Sweden (van der Velde et al., 2013). Due to climate change, an increase in temperature and more variability in precipitation has been observed during the last century (IPCC, 2013).

Both permafrost and glaciers are present in parts of the Scandinavian mountain range with permafrost ranging from continuous over discontinuous, sporadic to isolated coverages (Christiansen et al., 2010). The influence of glaciers and permafrost on streamflow in Scandinavia is recognized and the impacts of climate change on the cryosphere are well studied (Sjöberg et al., 2013; Engelhardt et al., 2014; Fleming and Dahlke, 2014).

Daily streamflow data were acquired from the Swedish Meteorological and Hydrological Institute (SMHI, 2016), the Norwegian Environmental Institute and the Danish Centre for Environment and Energy. The stations in Norway were chosen from the reference hydrometric network and considered suitable for the purpose of this study (Fleig et al., 2013). The selection following the above-mentioned criteria, namely minimum of 50 years of continuous data and no major regulation within the catchment, resulted in 26 catchments in Sweden, 27 in Norway and 6 in Denmark (Table 1). Full records covering all data available were considered for each catchment with records ranging from 54 to 122 years. Furthermore, the 50-year common period 1961-2010 was applied to be able to compare among the catchments. The hydrological year was used for all analyses which is defined as October 1 through September 31 of the following year for the region. This is commonly used for regions where streamflow is rainfall-dominated since it allows for allocating the peak in the correct year.

2.2 Flood seasonality

Circular or directional statistics were used to assess flood seasonality (Mardia, 1975; Fisher, 1993; Pewsey, 2002; Cunderlik et al., 2004; Pewsey et al., 2013; Villarini, 2016). This allows for determining whether annual maximum daily flows occur around a certain time in the year and thus exhibit strong seasonality, or if occurrences of annual maximum daily flows are more spread across the year. Due to the importance of assessing flood seasonality, circular statistics have increasingly been used for water management purposes (Villarini, 2016; Blöschl et al., 2017). Circular statistics are based on the concept that data (such as the daily data considered here) can be presented on the circumference of a unit circle (Figure 1), providing both a graphical as well as a statistical measure for analysis (Pewsey et al., 2013). For that, each day is converted to radian angles and displayed on the circumference of a unit circle where each month represents an equal segment of the circle (Cunderlik et al., 2004). The hydrological year starts with October 1 at 0° (North direction) of a compass or circle and moves clockwise (e.g. January 1 is at 90°).

Generally, circular statistics are based on the null hypothesis that the data are evenly distributed around the circle (known as uniformity) and show no propensity for clustering in a dominant direction (Pewsey, 2002). The hypothesis of circular uniformity can be tested using the Rayleigh test and Rao’s spacing test (both of which were considered in this study). Rao’s spacing test is recommended because it is a more general test to assess uniformity (Pewsey et al., 2013). The Rayleigh test was used as well due to the *a priori* assumption that snowmelt-dominated catchments show strong seasonality and thus non-uniformity with one single peak of departure from uniformity. If the null hypothesis is rejected, the data depart from uniformity and must be tested further for asymmetric or reflective symmetric appearance using the asymptotic large-sample test for reflective symmetry with an unknown mean direction presented by Pewsey et al. (2013). All tests were performed at the 5% significance level.

The mean direction $\bar{\theta}$ of the data is useful to assess uniformity visually, but it has to be combined with the mean resultant length $\bar{R}$ to be able to quantify the spread of the data and thus the strength of the seasonality (Figure 1) (Villarini, 2016). $\bar{R}$ takes values from 0 to 1 where higher values represent a clustering of data points in a particular region of the circle (asymmetric) whereas low values represent data points that are more uniformly distributed along the circle. $\bar{R}$ combined with $\bar{\theta}$ can be displayed graphically on a vertical plane of the unit circle showing the strength of the seasonality from the center point in direction of $\bar{\theta}$ outward where the center point represents 0 and the outline represents 1 (arrows in Figure 1).

2.3 Cluster analysis

In order to get a better spatio-temporal overview of the potential flow regimes present in Scandinavia and help in summarizing the findings of this study, a clustering approach was used which allows the identification of regions of homogeneous flood occurrences. Ward's hierarchical cluster analysis was selected to characterize Scandinavian flow regimes. This approach minimizes the variance within a cluster and has previously been used to define flood regions (Ward, 1963; Mediero et al., 2015). The cluster analysis was done using the average flood occurrence over the common period 1961-2010 (defined here as the average of the days of the year when the maximum annual daily discharge occurred over the common period for each station) and the mean resultant length $\bar{R}$. We assumed the clustering to be constant over the region with regards to time based on these averages. The optimal number of clusters was determined using within-cluster sum of squares based on the hierarchical clustering (see Figure S1 of the supplementary material). The determination of the optimal number of clusters based on the average flood occurrence day and the mean resultant length $\bar{R}$ has some limitations (Cunderlik et al., 2004), and was therefore complemented by previous knowledge of the region, such as information on catchment properties and climate regions in Scandinavia. An example comparison of different optimal numbers of clusters is presented in the supplementary material (Figure S2). This allowed for defining four regions of different flood occurrences which provided a good overview of flow regimes present across Scandinavia and their connection to certain important local catchment characteristics (i.e. maximum elevation).

2.4 Trend statistics

In addition to circular statistics, which were used to determine the strength of flood seasonality across the region and to define regions of different flow regimes (using clustering), the Mann-Kendall trend test was applied to estimate possible changes in selected hydrological parameters. The Mann-Kendall trend test is a non-parametric trend test that is based on the assumption that the data are independent and monotonic (Douglas et al., 2000; Burn and Hag Elnur, 2002; Helsel and Hirsch, 2002; Yue et al., 2002a; Clarke, 2013). To determine whether a time series shows serial correlation, the Durbin-Watson test was applied (Durbin and Watson, 1950). The presence of serial correlation is a known limitation for trend studies, and accounting for serial correlation has been widely acknowledged as important to avoid false detections of trends (Yue et al., 2002b; Yue et al., 2003). Several alternative approaches have been suggested such as pre-whitening of the time series (Cunderlik and Ouarda, 2009) and using a modified Mann-Kendall trend test that specifically accounts for autocorrelation in the data (Hamed and Rao, 1998). In this study, the modified Mann-Kendall trend test was adopted from Hamed and Rao (1998), which first evaluates the data for the presence of autocorrelation and then adjusts the variance of the dataset before performing the rank correlation test (Kendall, 1938). Example results of a comparison between the original and the modified Mann-Kendall trend test are provided in Figures S3 and S4 of the supplementary material. All tests were performed at the 5% significance level (2-sided for the (modified) Mann-Kendall trend test).

More specifically, the Mann-Kendall trend test was applied to the following hydrological parameters at different time scales based on the original daily time series: the annual maximum daily flow [m^3/s] (flood magnitude), the day of the hydrological year (DOHY) at which the annual maximum daily flow occurred (also referred to herein as flood occurrence), and the seasonal maximum daily flows [m^3/s]. The seasons are defined as winter (DJF; December through February), spring (MAM; March through May), summer (JJA; June through August) and autumn (SON; September through November). In addition, mean flows were analyzed on all above-mentioned time scales. Given the impact of time series length on the outcome of a trend statistic, a multi-temporal trend analysis was additionally computed on the longest records available for each cluster. This uses a moving-window approach, where the (modified) Mann-Kendall trend test is computed for every possible time series (different lengths and different start/end years) with a minimum of 10 years of data.

To explore impacts on water management, this study further took a closer look at the spring snowmelt peak in catchments defined as snowmelt-dominated in the cluster analysis (regions 1 and 4 in Figure 2, n = 30). These catchments are characterized by a single snowmelt peak in spring or summer. The snowmelt peak was defined from the hydrological records as the period between snowmelt onset and reaching summer base flow, where snowmelt onset was defined with the algorithm used for spring pulse onset introduced by Cayan et al. (2001). The Mann-Kendall trend test was applied to the time series for the duration, the volume and the fraction of the snowmelt peak. The duration is defined as the number of days from snowmelt onset to reaching summer base flow, the volume of the snowmelt peak denotes accumulated flows [m^3/s] for the duration of the snowmelt and the fraction of the snowmelt peak is defined as the percentage of annual flow.

Additionally, to provide some simple assessment of trend magnitudes, linear rates of change were estimated for annual mean and maximum daily flows and flood occurrence by fitting a linear model based on the Thiel-Sen slope estimator using $y=mx+b$ where y is the maximum annual daily flow [m^3/s], x is time (year), m is Sen's slope and b is the intercept (Hannaford and Buys, 2012). This is preferred over a linear regression model since Sen's slope is less sensitive to outliers than a linear regression model (Stahl et al., 2010). Relative rates of change over a 50-year period were calculated from that linear model as percentage of change which allows an easier interpretation of changes and a comparison among catchments.

3 Results

3.1 Coherent flood regions across Scandinavia

Distinct regions of coherent flood occurrence could be identified using hierarchical clustering (Figure 2). Region 1 (yellow dots) denoted snowmelt-dominated catchments with flood occurrences in spring (May to mid-June). Region 2 (green dots) represented temperate rainfall-dominated flow regimes with flood occurrences during autumn and winter (October through March). Those latter catchments could be characterized by an asymmetric (wet period during autumn and winter, present in the south) or reflective symmetry (smaller snowmelt peak in spring and larger rainfall peak in autumn, present along the northern Atlantic coast), both showing a similar mean direction and mean resultant length. Region 3 (blue dots) were low-elevation catchments (maximum elevation less than 1600 m a.s.l.) which are snowmelt-dominated, but less pronounced than region 1 and with autumn rainfall events. Lastly, region 4 (red dots) denoted a mix of glacier and snowmelt-dominated catchments characterized by flood occurrences in summer (late June to August). These catchments are characterized by significant glacier coverage (35 and 40% of catchment area, respectively) or a combination of high latitude (more than 66° N) and high elevation (maximum elevation more than 1600 m a.s.l.), which made the distinction to purely snowmelt-dominated catchments (i.e. region 1).

3.2 Flood seasonality using circular statistics

Exploring the strength of flood seasonality using circular statistics, mean resultant lengths $\bar{R}$ ranged between 0.17 and 0.99 with an average of 0.72 across Scandinavia (Figure 3a). Higher values indicate stronger seasonality such as present for snowmelt-dominated catchments (regions 1 and 4, $\bar{R} > 0.7$), whereas lower values represent a more uniform flood seasonality such as present in the catchments with a mixed snowmelt/rainfall flow regime in region 2 (more uniform or reflective symmetry, $\bar{R} < 0.7$). Mean directions (Figure 3b) were in agreement with flood occurrences and thus the clustering showing the distinction between snowmelt-dominated (spring and summer occurrences, regions 1 and 4) and rainfall-dominated catchments (autumn and winter occurrences, regions 2 and 3).

Both Rao’s spacing test and the Rayleigh test showed that the hypothesis of uniformity could be rejected and there was a significant departure from uniformity in all catchments ($p < 0.05$). This indicates that there is seasonality in flooding across Scandinavia, even for catchments characterized by a rainfall-dominated flow regime without a pronounced single peak in the annual hydrograph (Figure 3c). For those catchments asymmetry was still present, but it was more spread across the wet period corresponding to several months rather than concentrated to a few weeks such as for snowmelt-dominated catchments resulting in a lower mean resultant length $\bar{R}$.

3.3 Annual parameters

Looking at the results of the trend analysis, only few catchments exhibited significant trends for annual parameters (Figures 4 and 5, Table 2). This corroborates the outcomes of previous studies (e.g. Wilson et al., 2010; Matti et al., 2016) who found variable trends in streamflow signatures (mean and maximum annual daily flows) across northern European catchments and only few stations that exhibited a clear signal of change resulting in a significant trend. Considering the common period 1961-2010, significant changes pointed consistently toward an earlier flood occurrence whereas flood magnitude showed more variable trends and fewer catchments exhibited a significant change (Figure 4a). Those catchments are mainly located along the Scandinavian mountain range in region 1. For flood magnitude, 10% of the catchments showed a significant trend with 50% increasing (decreasing), whereas 27% of the catchments exhibited a significant trend in flood occurrence out of which 88% pointed toward an earlier occurrence. Linear rates of change over 50 years ranged from -32.6% to +41.8% for flood magnitude and from -7.7% to +34.5% for annual mean flows. In particular, catchments located in the Scandinavian mountain range (region 1) showed more significant changes in flood occurrence (44% of the catchments in region 1 showed a significant decreasing trend). Whereas this concerns significant increasing trends (later flood occurrence), significant decreasing trends were found for the rainfall-dominated region 4 in southern Sweden.

Considering full periods of record, significant trends showed the discrepancy between snowmelt-dominated and rainfall-dominated catchments with increasing trends in flood magnitude for catchments located in the south and the west of the study area (region 2). For the snowmelt-dominated catchments of region 1 located in the north and at higher elevations (Figure 4b), a decrease in flood magnitude was typically observed. Across the whole study region, 15% of the catchments showed a significant increasing trend and 10% exhibited a significant change toward a lower flood magnitude. Analysis of annual flood occurrence revealed an earlier occurrence of the annual flood peak in general. This supports the argument that a change in flow regime has occurred in catchments predominantly located in the snowmelt-dominated region 1. A significant decreasing trend in flood occurrence pointing toward an earlier timing of the annual flood peak showed 25% of the catchments, whereas only one catchment exhibited a significant increasing trend in flood occurrence. Considering annual mean flows, 37% of the catchments showed a significant (increasing) trend (Figure 5). Those catchments were located in close proximity to the coast line or in southern Scandinavia, and thus characterized by rainfall-dominated or mixed flow regime (regions 2 and 3). The variable trends in flood magnitude observed for the common period were corroborated over the full periods of record with few catchments exhibiting significant trends and those were both increasing and decreasing.

In order to assess the magnitude of the changes, linear rates of change over a 50-year period were calculated. Results showed that flood occurrence ranged from 33 days earlier to 40 days later over that 50-year period, where changes toward a later flood occurrence were found in catchments located in southern Sweden. Linear rates of change for flood magnitudes ranged from -17.2% to +36.3% over a 50-year period and from -15.7% to +49.3% over a 50-year period for annual mean flows.

Looking into changes in snowmelt peak characteristics (Figure 6), only few catchments exhibited significant trends in either of those characteristics over both the common period and the full periods of record with percentages of catchments showing a significant trend ranging from 3% (1 catchment) to 10% (3 catchments) considering all catchments (Table 3). Considering the common period, linear rates of change over 50 years ranged from 33 days shorter to 61 days longer for the peak duration, -45.6 to +74.9% for the snowmelt peak volume and -41.0 to +62.0% change for the snowmelt peak fraction. Region 4 in particular, exhibited significant trends over the common period, with significant increasing trends in all parameters. In contrast, only one catchment in region 1 (not the same catchment for all parameters) showed a significant but decreasing trend in all snowmelt peak parameters.

Considering full record periods, linear rates of change were consistently lower ranging from 8 days earlier to 6 days later for peak duration, -24.0% to +25.8% for peak volume and -33.0 to +17.6% for snowmelt peak fraction. All significant trends were found for catchments located in region 1 with both increasing and decreasing trends for snowmelt peak duration and volume, and consistently decreasing trends for the fraction of the snowmelt peak.

3.4 Seasonal maximum daily flows

Splitting up the time series into the four seasons, there was fair agreement between the results of the seasonal analysis and the changes detected in annual parameters. Generally, more catchments exhibited significant trends looking into seasonal parameters. Seasonal maximum daily flow magnitudes showed a general increasing trend in winter, spring and autumn, while a decreasing trend was identified in summer considering the common period 1961-2010 (Figure 7a, Table 4). For the spring season, 13% of the catchments showed a significant trend out of which 77% were increasing. For summer, 14% overall with 86% significant decreasing trends were detected, whereas for winter 20% of the catchments showed significant changes, all pointing toward decreasing flows. For autumn, 7% of the catchments were found to exhibit significant changes out of which 71% were changes toward higher flows. Regional patterns agreed with the results for the full records with most changes in the Scandinavian mountain range and the Norwegian west coast, ranging across all hydrological regions. Considering the common period, summer and winter showed the most changes, whereas in contrast to the full periods in spring more variable changes were detected.

The results for the full periods of record agreed with the common period and showed consistently a higher percentage of significant trends (Figure 7b). For spring, 34% of the catchments were found to exhibit significant trends out of which 90% were increasing trends. For summer, 29% of the catchments showed significant trends, with 82% decreasing trends. Catchments with an increasing trend in summer maximum flows were all located in southern Sweden and Denmark (region 2). For autumn, 22% of the catchments showed a significant trend out of which 77% were increasing trends. The catchments showing decreasing autumn trends were all located in the Scandinavian mountain range or at the west coast of Norway (predominantly region 2). Finally, for the winter season 24% of the catchments were found to exhibit a significant trend with 93% identified as increasing trends ranging across all hydrological regions.

3.5 Seasonal mean daily flows

For seasonal mean daily flows over the common period, the same patterns emerged as for maximum flows, with increasing trends in spring, autumn and winter, and decreasing trends for summer (Figure 8a, Table 5). The highest percentages of significant changes in mean flows were found for spring (39%) and winter (46%) with only increasing trends for both seasons. For summer, 6% significant trends were observed with 50% increasing and decreasing trends. For autumn, 9% of the catchments showed significant changes over the common period with 78% increasing trends. It is remarkable that winter and spring showed high percentages of catchments in all regions exhibiting significant trends which is a strong indication for an increasing winter baseflow caused by a shift from snow to rain as winter precipitation.

The results for the full periods agreed with the results for the common period, although significant trends were observed for more catchments (Figure 8b). Overall, the percentage of catchments showing significant trends was higher for mean flows than for maximum flows. Also, for both winter and spring, all significant trends suggested an increase in streamflow. For spring, 61% and for winter 51% of the catchments exhibited a significant increasing trend. For summer, 27% showed a significant trend of which 63% were decreasing, whereas for autumn 27% of the catchments showed a significant trend of which 88% were increasing trends. Overall, spatial patterns were in agreement with the spatial distribution of significant trends in seasonal maximum daily flows with significant trends in all hydrological regions. Winter showed a contrasting spatial distribution of significant trends compared to summer. Also, all significant decreasing trends in summer were observed in catchments located in the Scandinavian mountain range (mostly region 1).

4 Discussion

4.1 Large-scale first order control

Circular statistics were shown to be suitable for quantifying flood seasonality across Scandinavia and revealed regional differences in both mean direction (flood occurrence) and mean resultant length (flood magnitude) within a regional clustering framework (Figure 2). Strong seasonality in the snowmelt-dominated catchments of region 1 was characterized by an asymmetric occurrence whereas mixed snowmelt/rainfall regimes (region 3) showed a reflective symmetry. The rainfall-dominated catchments (region 2) exhibited a less pronounced seasonality and skewed more toward uniformity with a balanced wet and dry period. Seasonality of the different flow regimes and corresponding symmetry (or lack thereof) is consistent with studies investigating flood generating mechanisms across Norway and the United States (Vormoor et al., 2015; Berghuijs et al., 2016; Villarini, 2016).

The presence of distinct and consistent regions of flood occurrence as well as flow regime suggests that large-scale controls dominate across Scandinavia. With large-scale, we mean climate patterns and in particular, atmospheric circulation patterns over the North Atlantic Ocean causing consistent results for seasonal trends. This corroborates the findings of previous studies on large-scale atmospheric circulation patterns over the Atlantic showing their impacts on Scandinavian streamflow (Busuioc et al., 2001; Hall et al., 2014). This large-scale control is also reflected in the records of the catchments with the longest available record period for each region (Figure 9). The cyclic behavior in flood magnitude time series is likely caused by atmospheric circulation patterns such as the North Atlantic Oscillation. Furthermore, looking at the record of the catchment in region 4 in Figure 9, the influence of the record period considered can be shown. Whereas considering the full record period gives a significant decreasing trend (solid line, p-value < 0.01), an increasing trend was the result considering the common period 1961-2010 (dashed line, p-value 0.08). This highlights the sensitivity of trends in general, but also of the common period considered in this study. It has been shown that the 1960ies and 1970ies were a dry period across Sweden, and it is well known that we are currently in a wet period (Kundzewicz et al., 2014; Lindström and Bergström, 2004; Matti et al., 2016). Therefore, interpretations of trend results with those start and end dates should be made with care, and preferably combined with the results of longer records (such as the full periods in this study). Furthermore, this highlights the importance of the large-scale climate control causing cycles leading to both significant increasing and decreasing trend results depending on the time period and record length considered such as shown here through the multi-temporal trend analysis (Figure 9 bottom row).

The increasing trends in seasonal and annual parameters found for the rainfall-dominated south in both seasonal and annual analyses for rainfall-dominated southern Scandinavia (Denmark and southern Sweden, region 2), correspond to increasing annual precipitation observed for Scandinavia and other temperate regions such as the UK and the central US

(Lindström and Alexandersson, 2004; Burn et al., 2012; Hannaford, 2015; Mallakpour and Villarini, 2015; Slater and Villarini, 2016). An increase in both magnitude and frequency of rainfall-generated floods has been observed for those areas which agrees with the findings of this study and shows that climate (i.e. precipitation) provides a first order control on streamflow response.

In contrast to Berghuijs et al. (2014) who found decreasing mean annual flows for catchments shifting from snowmelt-dominated to rainfall-dominated across the United States, this study showed that an increase in mean annual streamflow can be expected for Scandinavia (Figure 5). Likewise, this would have implications for water management strategies, especially for hydro power and flood management. Contrasting trends are possibly caused by large-scale atmospheric circulations which have differing effects on North America and Europe as shown by Kingston et al. (2006). An increase in precipitation is projected for northern Europe which has the power of compensating the deficiency in snow accumulation during winter caused by higher temperature (Callaghan et al., 2010). In contrast to northern Europe where a shift in flow regime and concurrent significant changes in annual streamflow is projected, more variability is expected in North American streamflow in response to climate circulations explaining the results found by previous studies (Cunderlik and Ouarda, 2009; Berghuijs et al., 2014; Hall et al., 2014).

4.2 Local second order control

Looking at the changes more closely and taking into account annual trends, our results suggest, especially for snowmelt-dominated catchments in Scandinavia (regions 1 and 4), that despite the large-scale signal local controls modulate the streamflow response as climate changes. This causes the locally variable trends in streamflow which is consistent with previous research on northern Swedish catchments (e.g. Matti et al., 2016). This local-scale modulation of hydrologic response via landscape structure is common across catchment-scale investigation (i.e. Broxton et al., 2009). Here, it is the dynamic nature of the cryosphere as a catchment-changing structural element that comes into play (Lyon et al., 2009). In cold regions such as northern Scandinavia and the Scandinavian mountain range, permafrost and glaciers are known to impact streamflow and especially the flow regime (Dahlke et al., 2012; Sjöberg et al., 2013; Engelhardt et al., 2014). Decreasing trends in summer flows have, for example, been shown to indicate permafrost thaw (Walvoord and Striegl, 2007; Lyon et al., 2009), whereas glaciers dampen the spring flood and prolong the melt season with a peak in late summer such as shown for catchments in region 4 (Dahlke et al., 2012). In addition to the shift of the hydrograph peak from summer to spring, permafrost thaw would explain the decreasing summer flows observed in this study (e.g. Sjöberg et al., 2013).

Glaciers impact streamflow through delaying and prolonging the annual snowmelt peak causing a characteristic flow regime and leading to negative trends, especially for summer flows such as previously shown for glacierized catchments both in North America and Europe (Birsan et al., 2005; Stahl and Moore, 2006; Casassa et al., 2009; Moore et al., 2009). Furthermore, large-scale climate impacts on streamflow in glacierized catchments have been explored across Norway and Canada where strong correlations have been found (Engelhardt et al., 2014; Fleming and Dahlke, 2014). In this study, catchments with a substantial amount of glacier coverage (35% and 40% of total catchment area, respectively) indicate that typical flow regime with a prolonged flood season during summer caused by glacial melt (the catchments of region 4 located further south).

Hence, there can be a seasonal variability in the role (extent) of landscape controls on modulating hydrologic response to large-scale forcing patterns such that consistent patterns emerge under certain periods (like spring flood) relative to other periods where landscape heterogeneities dominate (e.g. summer low flows) (Lyon et al., 2012). The regional consistency tempered with potential seasonal variability strengthens the argument that large-scale climate controls the first order streamflow response in Scandinavia suppressing a more local signal caused by local factors (i.e. glacier coverage, catchment elevation, presence of permafrost), which on the other hand causes intra-annual variability and differences in trends in response to climate change (Fleming and Dahlke, 2014). As such, it is crucial to distinguish between first and second order controls. Furthermore, our results highlight that there is a need to combine all modes of streamflow control to be able to fully capture the dynamic changes that can occur at regional scales and be relevant for adapting management strategies (van der Velde et al., 2014).

4.3 Empirical evidence of a shifting hydrograph

A clear distinction can be made between seasons where both maximum and mean daily flows showed similar patterns of change. Increasing streamflow during autumn and winter suggest that rainfall-driven floods are occurring more frequently which agrees with previous findings for Norwegian flow regimes (Vormoor et al., 2016). Decreasing trends in summer flows could be expected, especially for high latitude catchments which show a mean flood occurrence in late spring/early summer. Furthermore, decreasing trends in summer flows have been reported by other studies showing that permafrost thaw and the loss of glaciers cause a decrease in summer floods due to a higher storage capacity of the ground (Dahlke et al., 2012; Sjöberg et al., 2013; Matti et al., 2016). Additionally, decreasing trends in summer flows can be explained by the earlier occurrence of the flood peak, specifically the shift of the peak of the annual hydrograph from early summer (June) to spring (May). This corroborates the increasing trends found for spring which otherwise contradict a potential shift in flow regime.

Looking into changes in the spring snowmelt peak, only minimal changes were found with less than 10% of the catchments showing significance. Nonetheless, especially catchments of region 4 showed significant changes indicating that both glacierized and high elevation catchments are exhibiting largest changes in the spring snowmelt peak and are thus likely the most vulnerable for a change in flow regime if present trends continue. This is further supported by significant increasing trends in the duration of the snowmelt peak for catchments located in region 4 indicating a prolonged snowmelt season (Figure 6 and Table 3). Also, the decreasing trends in the fraction of the snowmelt peak for catchments located in region 1 corroborate those findings indicating the decreasing fraction of snowmelt, respectively a less pronounced snowmelt peak in spring. This could also explain the increasing annual flows concurrent with increasing autumn and winter flows which would have profound implications on water management strategies with higher flows and thus implications for reservoirs (Barnett et al., 2005).

The results for spring also emphasize the importance of combining a seasonal analysis with another time scale (such as the annual analysis used in this study) to be able to allocate the flood peak in the right season. This is especially true for flood seasonality, where examining 3-month seasons or annual values separately could possibly lead to misinterpretations of ongoing processes indicating streamflow parameters to change. For example, if focusing on annual values only, a shift in flow regime might be missed due to the dominant snowmelt peak in spring which represses the detection of a potential increase in the autumn rainfall peak. Alternatively, focusing on 3-month seasons only could lead to misinterpretations if the annual peak switches from one season to another during the course of the study period (i.e. moves across the calendar divide between seasons). The results for annual flood occurrences confirm these findings showing significantly earlier annual flood occurrences for 25% of the catchments (Table 2). This is in agreement with other studies that additionally found earlier onset of snowmelt as indicator for a shift in flow regime (Stewart et al., 2005; Matti et al., 2016). Those findings highlight the importance of combining seasonal and annual values for both flood magnitude and occurrence to capture the system response. This study showed that combining trend analysis with circular statistics provides a useful tool to assess changes in flood seasonality capturing the system more completely.

However, in terms of potential uncertainty, another factor needs to be considered. Specifically, the choice of annual maximum daily flows to approximate floods over another metric such as a peak-over-threshold (POT) approach in this study could limit our findings to

551 some extent. There is a possibility that in some years, the maximum flow may not represent
552 an actual flood event. In addition, several floods of higher return period could occur in a given
553 year, but only the largest flow would be recognized by an approach using annual maxima.
554 However, for the purpose of this study and in line with the approach used in Villarini (2016)
555 for the United States, annual maxima have been selected. Cunderlik et al. (2004) showed that,
556 for non-uniformly distributed flow regimes such as present across all of Scandinavia, annual
557 maxima and POT perform similarly. Especially for pronounced single peak flow regimes such
558 as the snowmelt-dominated regime, annual maxima are often preferred over a POT approach.
559 Whereas most studies so far have used either one approach or the other (e.g. Cunderlik and
560 Ouarda (2009) used annual maxima, Hannaford and Buys (2012) used flood quantiles and
561 Vormoor et al. (2016) used a POT approach), it would be interesting to compare those two
562 methods to assess their strengths for assessing flood seasonality in northern environments
563 such as done for Wales by Macdonald et al. (2010). However, such a comparison is outside
564 the scope of this study and requires further research.

565 **5 Concluding remarks**

566 Changes in seasonal streamflow were predominant compared to changes in annual streamflow
567 across Scandinavia. Seasonal changes indicate a shift in flow regime which manifested itself
568 through decreasing summer flows and concurrent increasing flows in autumn and winter. It
569 appears that both mean and maximum daily flows are changing across Scandinavia where
570 differing patterns could be detected comparing snowmelt-dominated catchments (i.e. those
571 located in the Scandinavian mountain range) and rainfall-dominated catchments (i.e. southern
572 Scandinavia and Norwegian Atlantic coast). The rainfall-dominated catchments of region 2
573 further appear to experience a general increase in streamflow, which is in line with recent
574 increases in precipitation across that region.

575 Streamflow control and thus a shift in flow regime appears manifested through a large-scale
576 first order control (i.e. climate, atmospheric circulation patterns) in combination with local

577 second order flow control (i.e. catchment properties). The manifestation of those controls is changing inter-seasonally as well as over longer time periods which makes it difficult to predict future conditions, especially for snowmelt-dominated and mixed snowmelt/rainfall regions. Further research is needed to get an improved understanding of changes in streamflow as well as interactions of climate, streamflow response and catchment properties. Using a combination of circular statistics and trend analysis allows for assessing flow regime changes and provides a basis for deciphering underlying mechanisms, and we showed that this approach is capable of showing a shift in flow regime such as predicted by trend analysis on annual streamflow as well as projections of future streamflow.

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Figure Captions

Figure 1: Schematic explaining circular statistics where the black arrow indicates a combination of mean sample direction $\bar{\theta}$ (red arrow in figure c) and mean resultant length $\bar{R}$ (direction and length of the arrow, respectively, where a longer arrow indicates a stronger seasonality). **a)** represents a uniform symmetry which is characterized by a low $\bar{R}$ and average flood occurrences that are distributed throughout the year. **b)** represents a reflective symmetry with two peaks (spring snowmelt and autumn/winter rainfall) and **c)** represents asymmetry (one single peak, concentrated to a short time period).

Figure 2: Hydrological regions defined based on a cluster analysis of the average timing of the annual flood peak. Rose diagrams represent catchments that exemplify the hydrological regime of each region. Yellow dots (region 1) represent snowmelt-dominated catchments (spring peak flow), green dots (region 2) are winter rainfall catchments, blue dots (region 3) represent a low-elevation mixed snowmelt-rainfall regime and red dots (region 4) represent a special case of snowmelt-dominated catchment with a less pronounced and late summer peak flow. The dotted lines enclose the regions defined with the cluster analysis.

Figure 3: Results of the circular statistics analysis where **a)** shows mean resultant length $\bar{R}$ where high values indicate strong seasonality, **b)** represents the average timing of the annual flood peak over full periods of record (sample mean direction $\bar{\theta}$) and **c)** represents the results from the asymptotic test for reflective symmetry with unknown mean direction where blue symbols represent a rejection of the null hypothesis (5% significance level) and thus an asymmetric distribution and red symbols represent reflective symmetry. The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2.

Figure 4: Trends in magnitude (MAG) and occurrence (OCC) of annual maximum daily flows over **a)** common period 1961-2010 and **b)** full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01- 0.05, 0.05 - 0.1, $p > 0.1$) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level $\alpha = 0.05$. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels

from Figure 2. Pie charts show the percentage of catchments with significant trends at α = 0.05 across Scandinavia.

Figure 5: Trends in annual mean daily flows over **a)** common period 1961-2010 and **b)** full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01- 0.05, 0.05 - 0.1, $p > 0.1$) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level α = 0.05. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2. Pie charts show the percentage of catchments with significant trends at α = 0.05 across Scandinavia.

Figure 6: Trends in snowmelt peak characteristics over **a) – c)** the common period 1961-2010 and **d) – f)** full periods of record for the catchments considered (regions 1 and 4, n = 30) using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01-0.05, 0.05 - 0.1, $p > 0.1$) are shown for snowmelt duration (**a) and d)**), fraction of the snowmelt peak (**b) and e)**) and snowmelt peak volume (**c) and f)**). Markers with a black outline indicate significant trends at significance level α = 0.05. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2.

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Figure 9: Catchments with the longest record available for each hydrological region (1-4). The top row represents the time series of flood magnitude considered for the Mann-Kendall trend test. The bottom row shows the multi-temporal trend analysis based on the Mann-Kendall trend test with a minimum length of 10 years (diagonal). The solid black line represents areas of significant Mann-Kendall trend results (p-value < 0.1).

Tables

Table 1: Summary of data and catchment characteristics.

Country	Number of catchments used	Area [km^2]	Latitude	Longitude	Record period available	Data source
Sweden	26	2-33,930	55.95-68.37°N	12.13-24.06°E	1908-2014 (54-106 years)	SMHI (vattenweb.se)
Norway	27	7-4,425	58.40-68.41°N	4.94-15.71°E	1892-2014 (73-122 years)	NVE
Denmark	6	104-1,055	55.26-57.16°N	8.71-11.38°E	1918-2014 (81-97 years)	DCE at Aarhus University

Table 2: Changes in annual flood magnitude, flood occurrence and annual mean flow for the common period 1961-2010 and full periods of record available using the Mann-Kendall trend test. Percentages of catchments showing a significant trend ($p < 0.05$) are shown for each hydrological region and each country. Triangles indicate increasing or decreasing trends and n is the number of catchments considered for each hydrological region or country, respectively.

		Common period 1961-2010						Full periods of record					
		Magnitude [%]		Occurrence [%]		Mean [%]		Magnitude [%]		Occurrence [%]		Mean [%]	
	n	▲	▼	▲	▼	▲	▼	▲	▼	▲	▼	▲	▼
Region 1	25	4	8	0	44	24	0	8	8	0	44	24	0
Region 2	22	5	0	9	0	23	0	23	24	5	9	55	0
Region 3	7	14	14	0	43	0	14	29	0	0	14	43	0
Region 4	5	0	0	0	0	80	0	0	20	0	20	20	0
Sweden	26	4	4	8	27	27	0	8	0	4	35	27	0
Norway	27	7	7	0	26	26	4	15	19	0	19	41	0
Denmark	6	0	0	0	0	17	0	50	17	0	17	67	0

Table 3: Results from trend analysis on snowmelt peak characteristics using the Mann-Kendall trend test. Snowmelt duration (snowmelt onset until reaching summer base flow), snowmelt peak volume (accumulated flow) and fraction of annual flow are shown for common period 1961-2010 and full periods of record available. Percentages of catchments showing a significant trend ($p < 0.05$) are shown for each hydrological region and each country. Triangles indicate increasing or decreasing trends and n is the number of catchments considered for each hydrological region or country, respectively.

		Common period 1961-2010						Full periods of record					
		duration [days]		volume [%]		fraction [%]		duration [days]		volume [%]		fraction [%]	
	n	▲	▼	▲	▼	▲	▼	▲	▼	▲	▼	▲	▼
Region 1	25	0	4	0	4	0	4	4	12	4	4	0	12
Region 4	5	60	0	60	0	20	0	0	0	0	0	0	0
Sweden	18	6	6	6	0	0	6	0	17	6	6	0	17
Norway	12	8	0	17	8	8	0	8	0	0	0	0	0

Table 4: Changes in seasonal maximum daily flows for the common period 1961-2010 and full periods of record available using the Mann-Kendall trend test. 3-month seasons MAM (spring), JJA (summer), SON (autumn) and DJF (winter) were applied. Percentages of catchments showing a significant trend ($p < 0.05$) are shown for each hydrological region and each country. Triangles indicate increasing or decreasing trends and n is the number of catchments considered for each hydrological region or country, respectively.

		n	spring [%]		summer [%]		autumn [%]		winter [%]	
			▲	▼	▲	▼	▲	▼	▲	▼
Common period of record (1961-2010)	Region 1	25	12	4	0	4	8	0	16	0
	Region 2	22	0	5	5	9	0	0	14	0
	Region 3	7	14	0	0	57	14	14	43	0
	Region 4	5	40	0	0	0	0	0	20	0
	Sweden	26	12	0	4	4	8	0	8	4
	Norway	27	11	7	0	22	37	0	4	0
	Denmark	6	0	0	0	0	0	0	0	0
Full periods of record	Region 1	25	36	0	0	28	16	4	28	0
	Region 2	22	18	9	14	9	23	5	23	5
	Region 3	7	29	0	0	57	14	14	14	0
	Region 4	5	60	0	0	20	0	0	0	0
	Sweden	26	39	0	4	19	12	0	15	0
	Norway	27	22	4	0	33	11	11	19	0
	Denmark	6	33	17	33	0	67	0	67	17

Table 5: Changes in seasonal mean daily flows for the common period 1961-2010 and full periods of record available using the Mann-Kendall trend test. 3-month seasons MAM (spring), JJA (summer), SON (autumn) and DJF (winter) were applied. Percentages of catchments showing a significant trend ($p < 0.05$) are shown for each hydrological region and each country. Triangles indicate increasing or decreasing trends and n is the number of catchments considered for each hydrological region or country, respectively.

		n	spring [%]		summer [%]		autumn [%]		winter [%]	
			▲	▼	▲	▼	▲	▼	▲	▼
Common period of record (1961-2010)	Region 1	25	60	0	0	0	4	0	48	0
	Region 2	22	9	0	0	5	5	5	36	0
	Region 3	7	43	0	0	14	0	0	57	0
	Region 4	5	60	0	40	0	40	0	60	0
	Sweden	26	42	0	0	0	4	4	42	0
	Norway	27	44	0	7	7	7	0	59	0
	Denmark	6	0	0	0	0	17	0	0	0
Full periods of record	Region 1	25	76	0	4	24	20	4	52	0
	Region 2	22	41	0	23	5	27	5	50	0
	Region 3	7	71	0	0	43	14	0	43	0
	Region 4	5	60	0	0	0	40	0	20	0
	Sweden	26	62	0	4	23	15	4	50	0
	Norway	27	63	0	4	15	22	4	48	0
	Denmark	6	50	0	67	0	67	0	67	0

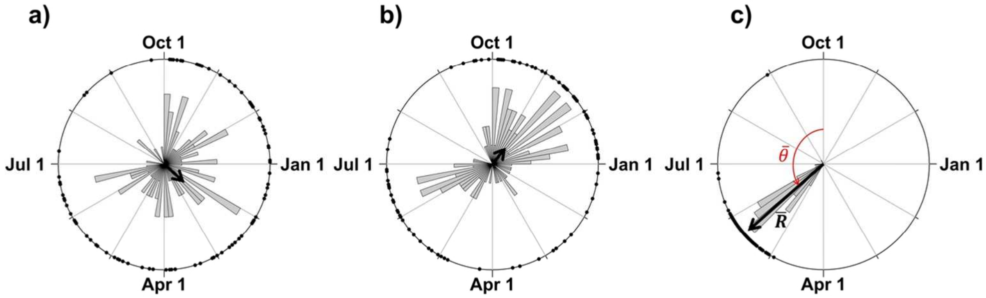

Figure 1 Schematic explaining circular statistics where the black arrow indicates a combination of mean sample direction θ¯ (red arrow in figure c) and mean resultant length R¯(direction and length of the arrow, respectively, where a longer arrow indicates a stronger seasonality). a) represents a uniform symmetry which is characterized by a low R¯and average flood occurrences that are distributed throughout the year. b) represents a reflective symmetry with two peaks (spring snowmelt and autumn/winter rainfall) and c) represents asymmetry (one single peak, concentrated to a short time period).

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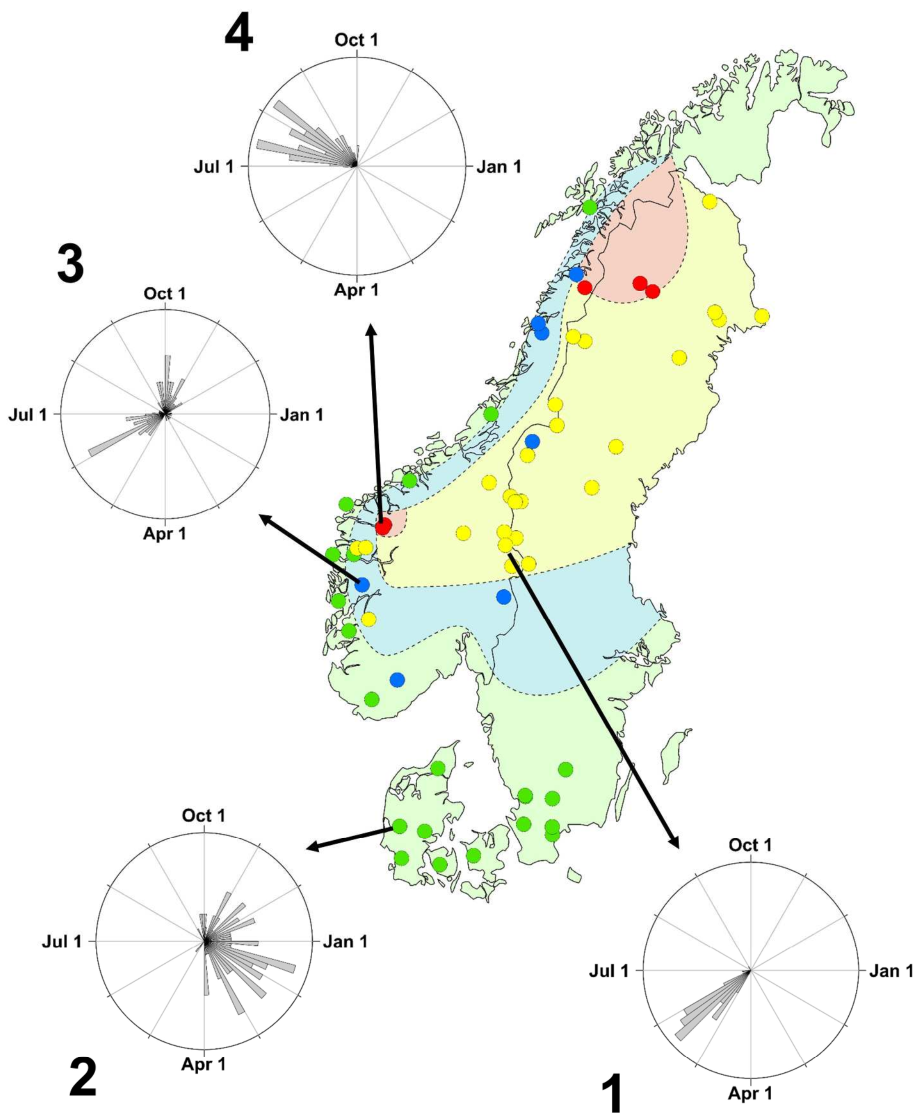

Figure 2 Hydrological regions defined based on a cluster analysis of the average timing of the annual flood peak. Rose diagrams represent catchments that exemplify the hydrological regime of each region. Yellow dots (region 1) represent snowmelt-dominated catchments (spring peak flow), green dots (region 2) are winter rainfall catchments, blue dots (region 3) represent a low-elevation mixed snowmelt-rainfall regime and red dots (region 4) represent a special case of snowmelt-dominated catchment with a less pronounced and late summer peak flow. The dotted lines enclose the regions defined with the cluster analysis.

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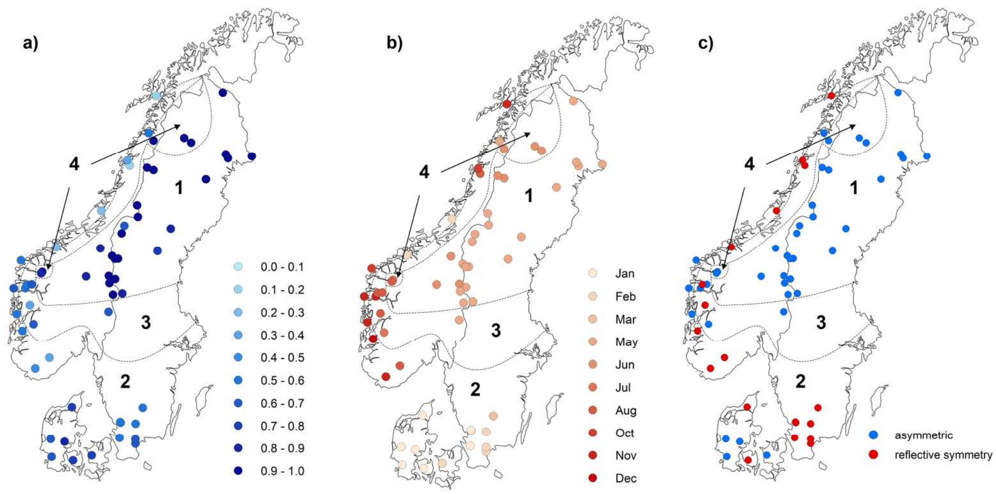

Figure 3 Results of the circular statistics analysis where a) shows mean resultant length $\bar{R}$ where high values indicate strong seasonality, b) represents the average timing of the annual flood peak over full periods of record (sample mean direction $\bar{\theta}$) and c) represents the results from the asymptotic test for reflective symmetry with unknown mean direction where blue symbols represent a rejection of the null hypothesis (5% significance level) and thus an asymmetric distribution and red symbols represent reflective symmetry. The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2.

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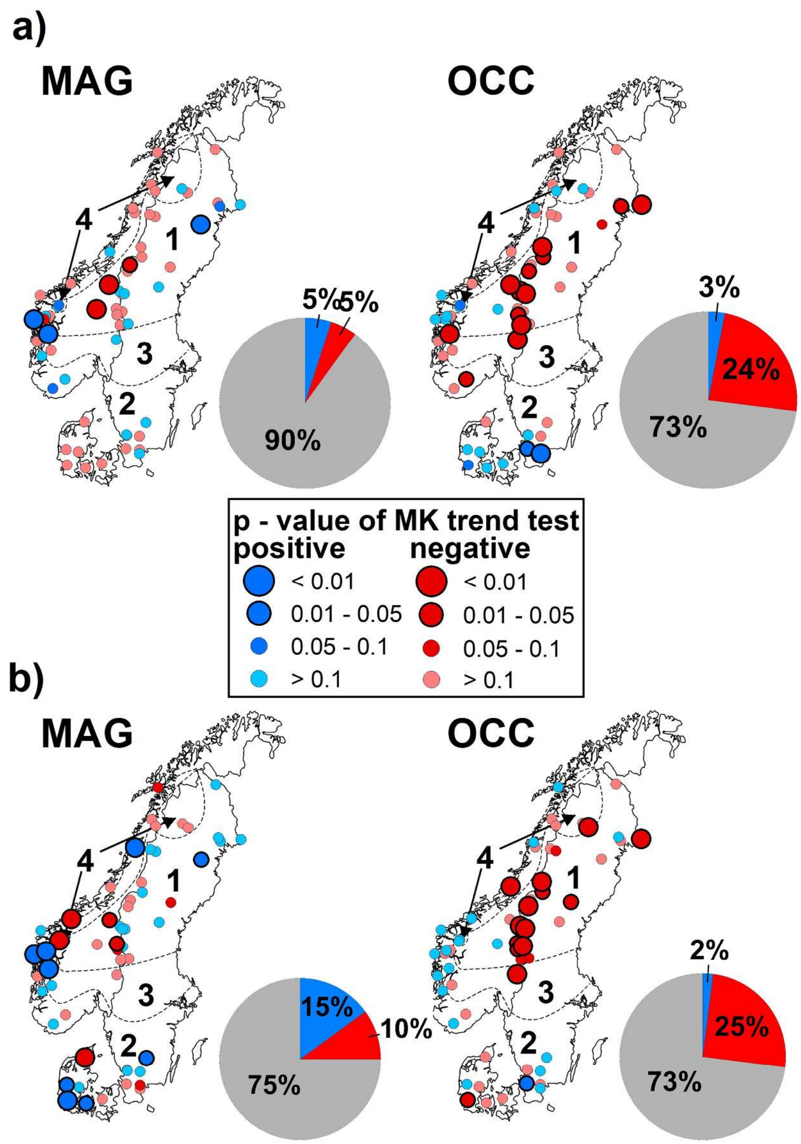

Figure 4 Trends in magnitude (MAG) and occurrence (OCC) of annual maximum daily flows over a) common period 1961-2010 and b) full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01- 0.05, 0.05 - 0.1, $p > 0.1$) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level $\alpha = 0.05$. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2. Pie charts show the percentage of catchments with significant trends at $\alpha = 0.05$ across Scandinavia.

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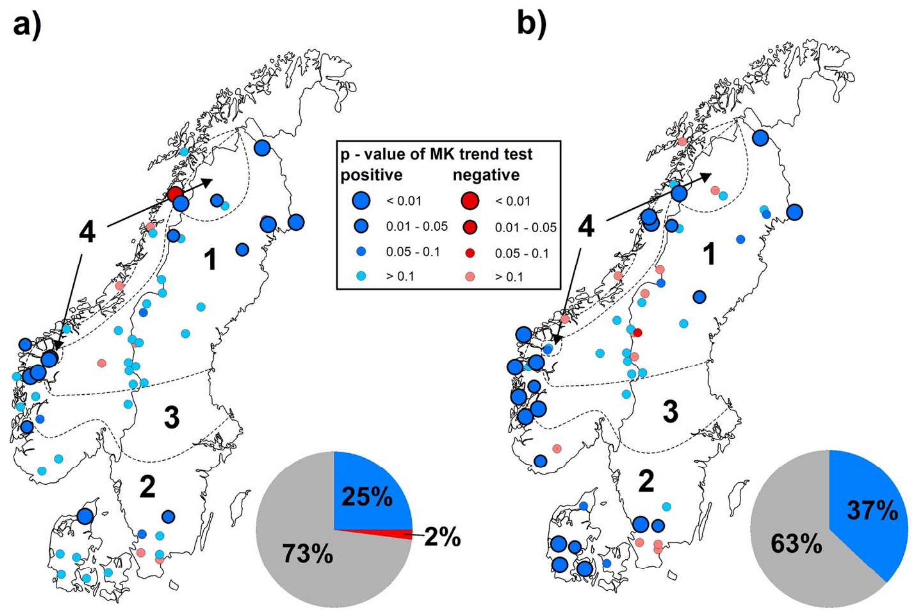

Figure 5 Trends in annual mean daily flows over a) common period 1961-2010 and b) full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends (p < 0.01, 0.01- 0.05, 0.05 - 0.1, p > 0.1) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level α = 0.05. Light blue (red) symbols indicate non-significant trends (p > 0.1). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2. Pie charts show the percentage of catchments with significant trends at α = 0.05 across Scandinavia.

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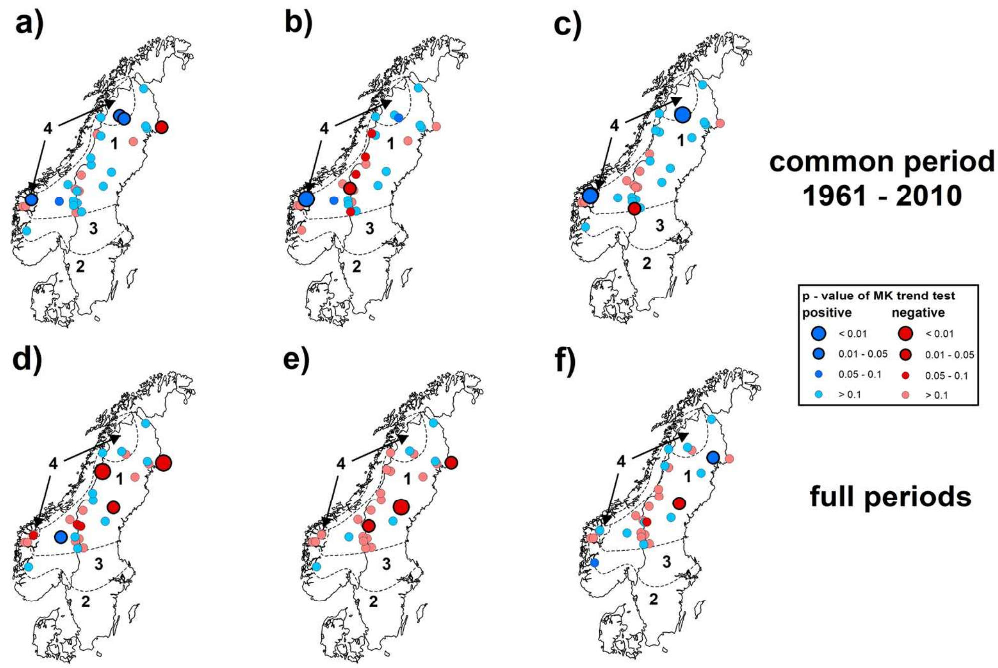

Figure 6 Trends in snowmelt peak characteristics over a) – c) the common period 1961-2010 and d) – f) full periods of record for the catchments considered (regions 1 and 4, n = 30) using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends (p < 0.01, 0.01- 0.05, 0.05 - 0.1, p > 0.1) are shown for snowmelt duration (a) and d)), fraction of the snowmelt peak (b) and e)) and snowmelt peak volume (c) and f)). Markers with a black outline indicate significant trends at significance level α = 0.05. Light blue (red) symbols indicate non-significant trends (p > 0.1). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2.

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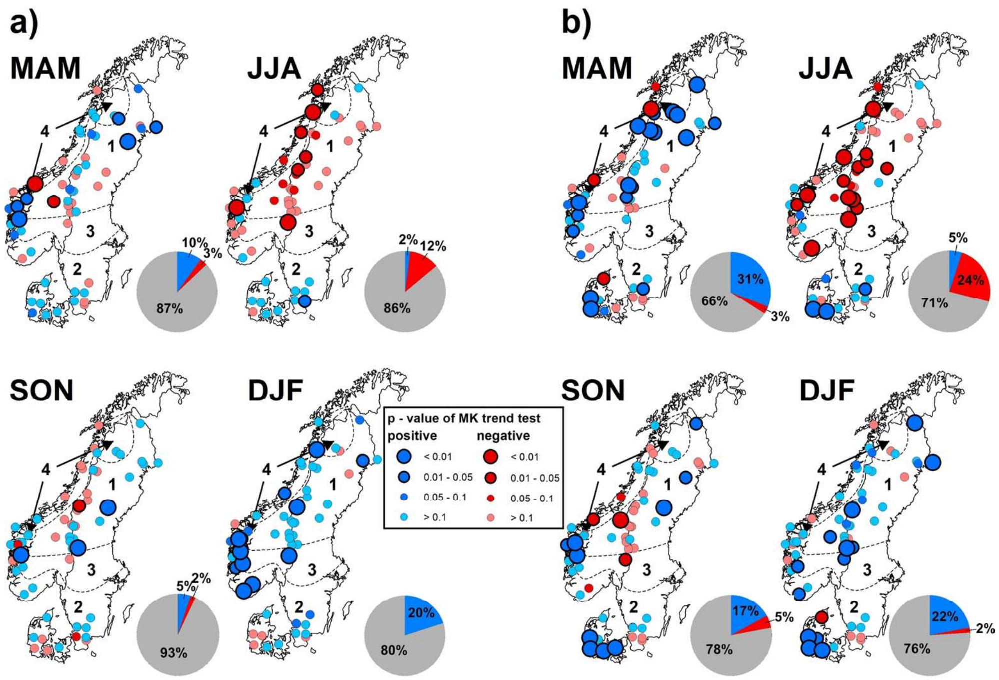

Figure 7 Trends in seasonal maximum daily flows over a) common period 1961-2010 and b) full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01- 0.05, 0.05 - 0.1, $p > 0.1$) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level $\alpha = 0.05$. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2. Pie charts show the percentage of catchments with significant trends at $\alpha = 0.05$ across Scandinavia.

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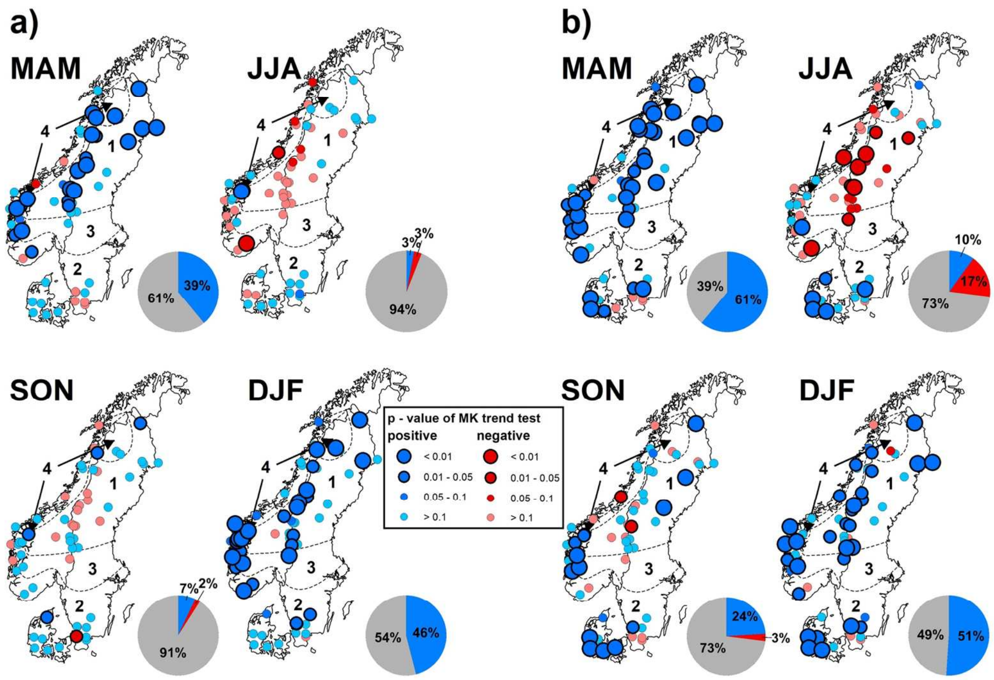

Figure 8 Trends in seasonal mean daily flows over a) common period 1961-2010 and b) full periods of record for each catchment using the Mann-Kendall trend test. Increasing (blue) and decreasing (red) trends ($p < 0.01$, 0.01- 0.05, 0.05 - 0.1, $p > 0.1$) are shown for spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Markers with a black outline indicate significant trends at significance level $\alpha = 0.05$. Light blue (red) symbols indicate non-significant trends ($p > 0.1$). The dotted lines enclose the regions defined with the cluster analysis and are labeled with the region labels from Figure 2. Pie charts show the percentage of catchments with significant trends at $\alpha = 0.05$ across Scandinavia.

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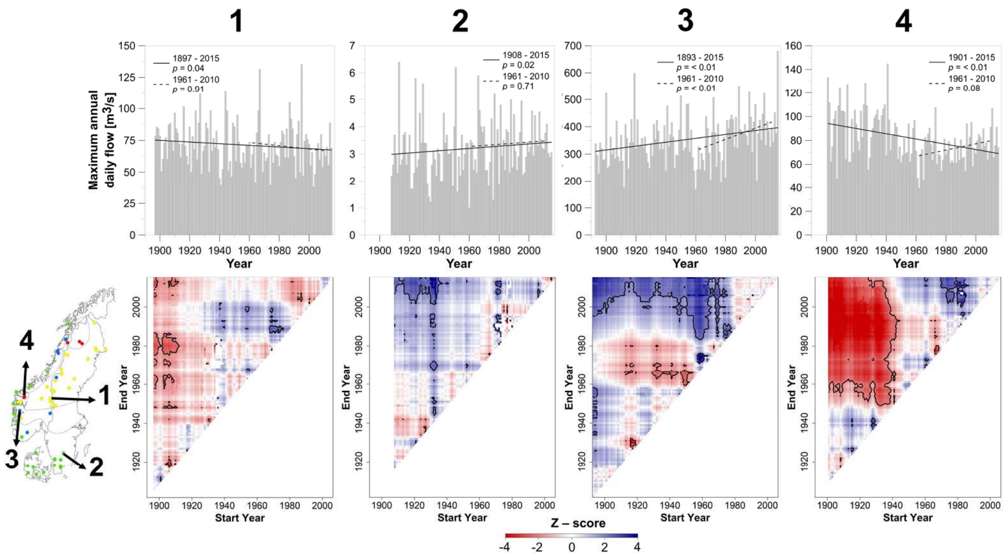

Figure 9 Catchments with the longest record available for each hydrological region (1-4). The top row represents the time series of flood magnitude considered for the Mann-Kendall trend test. The bottom row shows the multi-temporal trend analysis based on the Mann-Kendall trend test with a minimum length of 10 years (diagonal). The solid black line represents areas of significant Mann-Kendall trend results (p-value < 0.1).

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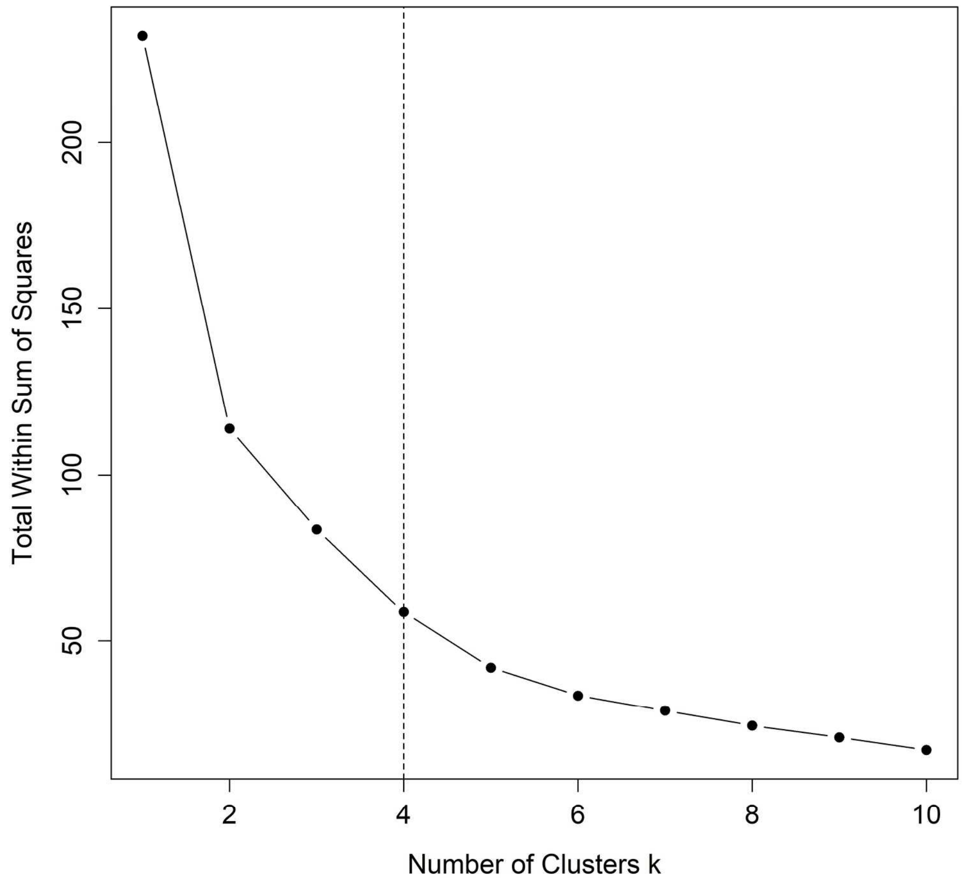

Optimum number of clusters determined using the total within-cluster sum of squares based on hierarchical clustering. Defining the optimum number of clusters as k=2 would result simply in a split of snowmelt-dominated (regions 1 and 4) vs. rainfall-dominated regions (regions 2 and 3).

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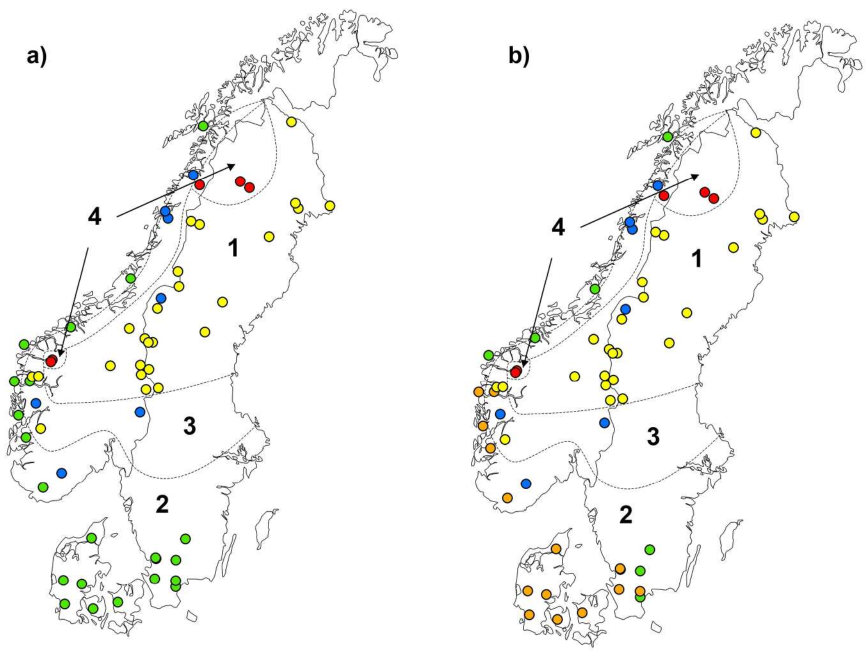

Example of optimal number of clusters with a) k=4 (as selected for the purpose of this study) and b) k=5, which merely splits region 2 into two different regimes (orange and light green markers) in comparison to a).

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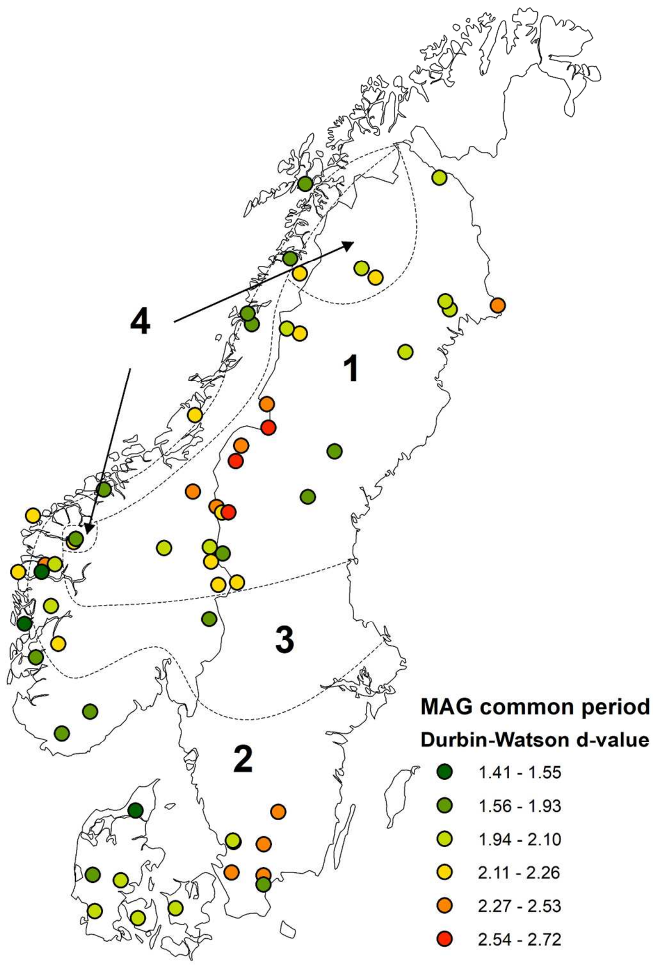
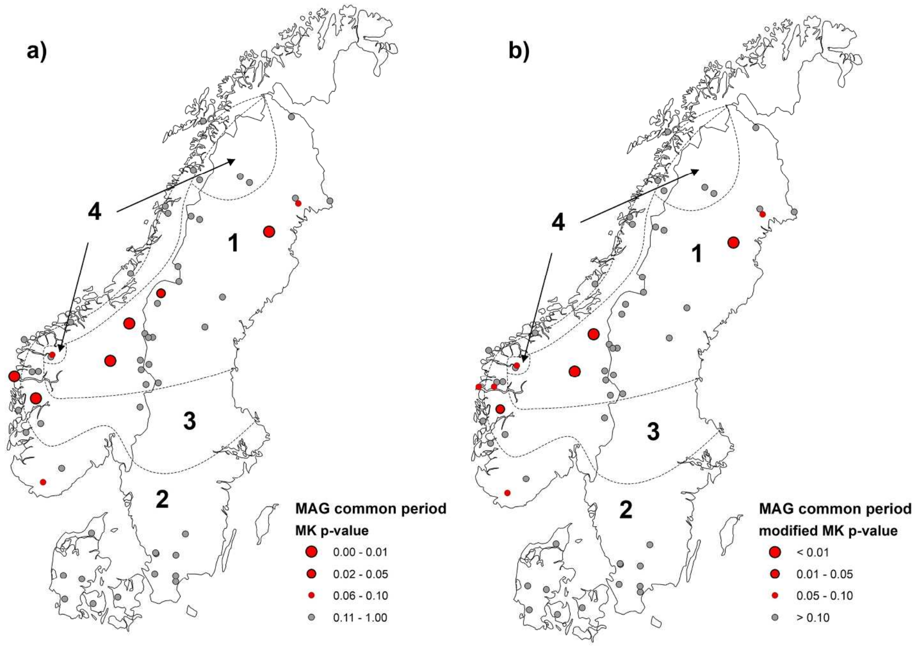


Durbin-Watson d-values for flood magnitude over the common period 1961-2010 to exemplify the serial correlation present in the data and the sub-sequent selection of the original or the modified Mann-Kendall trend test. The Durbin-Watson d-value indicates whether there is serial correlation present, and if it is positive (d-value < 2) or negative (d-value > 2) autocorrelation.

275x397mm (300 x 300 DPI)



The impact of serial correlation on the results of the trend test with the example flood magnitude over the common period 1961-2010. Most catchments showed no serial correlation and thus the original Mann-Kendall trend test was used for the trend analysis such as shown in a). Where serial correlation was present, the modified Mann-Kendall trend test (Hamed and Rao,1998) was used which resulted in the slightly different trend results shown in b).

210x148mm (300 x 300 DPI)