Trends in high peak flow generation across the Swedish Subarctic

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Preface

This Master’s thesis is Bettina Matti’s degree project in Physical Geography and Quaternary Geology at the Department of Physical Geography, Stockholm University. The Master’s thesis comprises 45 credits (one and a half term of full-time studies).

Supervisors have been Steve Lyon at the Department of Physical Geography, Stockholm University and Helen Dahlke at the Department of Land, Air and Water Resources, University of California, Davis, U.S. Examiner has been Jerker Jarsjö at the Department of Physical Geography, Stockholm University.

The author is responsible for the contents of this thesis.

Stockholm, 15 June 2015

Steffen Holzkämper
Director of studies
Abstract

There is growing concern for increased frequency of extreme events due to several severe floods and droughts occurring globally in recent years. Improving knowledge on the complexity of hydrological systems and interactions with climate is essential to be able to determine drivers and predict changes in the future. This is especially true in cold regions such as the Swedish Subarctic. This thesis explored changes in high peak flows and linked trends to climate. Trend analyses were applied on 18 catchments in the Swedish Subarctic over their entire periods of record and a common period (1990-2013) among the data to explore changes in flood magnitude, flood occurrence, mean summer flow, snowmelt onset and center of mass. Further, a flood frequency analysis was applied using the extreme value type I (Gumbel) distribution and selected flood percentiles were tested for stationarity. The results show the complexity of the hydrological system and interactions with climate. No clear overall pattern could be determined suggesting that changes are happening at catchment scale. Indications for a shift in flow regime from snowmelt-dominated to rainfall-dominated are evident with all significant trends pointing towards lower flood magnitudes in the spring flood, earlier flood occurrence and snowmelt onset, and decreasing mean summer flows. The shift in flow regime suggests that air temperature is more clearly reflected in streamflow than precipitation in the Swedish Subarctic. Decreasing trends in flood magnitude and mean summer flows are suggestive of permafrost thawing, which agrees with the increasing trends in the annual minimum flow. Long streamflow records can further link variability in streamflow to multidecadal atmospheric circulations over the North Atlantic. Most evident are changes towards lower mean summer flows (ten catchments significant at a 95% confidence interval) and earlier snowmelt onset (eight catchments significant). Trends in the selected flood percentiles show indications towards an increase in extreme events over the entire period (significant for four catchments), with all significant trends being positive. Over the common period, no pattern is notable and the sensitivity of trend analyses is evident.

Key words: flood generation, extreme events, climate change, Sweden, Subarctic, trend analysis, flood frequency analysis

Figure on the front page: Probability plot for the Stenudden catchment, from B. Matti.
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### Tables

**Table 1** Properties for the catchments considered in this thesis. The label of the gauging station used by SMHI, the catchment area (km$^2$), the mean elevation of the catchment (masl), the elevation range (minimum and maximum elevation, masl), the first full year of record and the length of the record period (years) are listed. The length of the record period represents the entire length, whereas the numbers in brackets represent the number of years with actual data (years with missing data are subtracted). The last year considered for all catchments is 2013.

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1 Introduction

The Earth’s environment is changing. Biotic factors like vegetation and ecosystem and abiotic factors like climate or hydrological conditions are interacting and shifting. The complexity of all systems involved is difficult to understand. This makes the manifestation of changes and feedbacks hard to predict. In high latitude regions, namely the Arctic and Subarctic, changes are even more pronounced. Increases both in mean annual air temperature and mean annual precipitation have been detected for the Arctic and Subarctic over the last century and the predictions for the 21st century show continued increasing trends in these areas (e.g. IPCC, 2013; Lindström & Alexandersson, 2004). In addition, studies in the Arctic and Subarctic have shown that permafrost is thawing and glaciers are retreating (Callaghan et al., 2013; Johansson et al., 2013, Dahlke et al., 2012). Further, the human population is growing and drinking water supply and flood protection are becoming increasing central water management purposes at high latitudes. There is growing concern that extreme events related to water resources such as droughts and floods are increasing through climate shifts coupled with landscape changes (Kundzewicz et al., 2014). Hall et al. (2014) pointed out the diversity of changes in the flow regimes in Europe and the interactions with humans and climate. Getting a better understanding of hydrological system functioning at the extremes and interactions between climate and hydrology are thus essential to be able to preserve human needs and protect infrastructure.

One approach to improve understanding is through data driven exploration. Understanding the past by investigating changes allows to connect findings from different fields of science and to detect feedbacks and interactions between systems. Trend analysis is an important and often used tool for such purposes, especially in hydrology (Hannaford et al., 2013). Through the development of measurement networks in the 20th century for hydrological and climatological parameters such as streamflow, air temperature and precipitation, continuous time series of daily observed data over periods of at least 25 years emerged in recent years. These relatively long time series allow for the analysis and the comparison of trends in the parameters measured. That can further be included in models for process parameterization allowing for predicting trends into the future (Hall et al., 2014). Especially in hydrology and climate science, owning to system complexity, knowledge of the system and feedbacks are essential to be able to get appropriate model results. This is especially important for water management purposes such as drinking water supply, flood protection and irrigation for agriculture, where stationarity can often be an issue (Milly et al., 2008).

Dealing with the past is thus an important part of research in hydrology and climate science. Since hydrological response can evolve both naturally and through anthropogenic influence, special care is needed when considering shifts and trends. Parallel to the improvement in measuring techniques, statistical models have been developing to allow for suitable analysis of observed data, detection of changes and isolation of process drivers. Especially in hydrology, modelling has become an important and powerful tool to determine trends and assess changes in extreme events such as droughts and floods (Hannaford et al., 2013). Numerous studies were computed in the second half of the 20th century to explore existing and/or develop new statistical methods for analyzing hydrological parameters, especially for extreme events (e.g. Clarke, 2013; Cayan et al., 2001; Chowdhury et al., 1991; Vogel, 1987). Also, statistical models have been tested and discussed on local and regional basis showing the difficulties in upscaling results from a catchment to a regional level, as well as the importance of the period of record analyzed (e.g. Hannaford et al., 2013; Woo & Thorne, 2008; Birsan et al., 2005; Stewart et al., 2005).
This thesis addresses these aspects collectively. Namely, it explores long time series of hydrological observations in northern Sweden. Specifically, statistical models of high peak flows are used to address trends in flood return periods over the past decades. The consistency (or lack thereof) in spatial patterns of flooding has the potential to yield information about the evolution of hydrological responses across this subarctic region.

1.1 State of research

There has been increased focus on extending knowledge of hydrological systems and interactions with climate in recent years. Studies have shown that both air temperature and precipitation have increased in the last century and will likely continue to rise in the future. Especially in the Arctic and the Subarctic, accelerated changes are predicted (e.g. IPCC, 2013; Callaghan et al., 2013; Lindström & Alexandersson, 2004). Simultaneously, the hydrological system and the cryosphere are changing. Glaciers are melting due to increased air temperatures. Permafrost thawing is a known phenomenon on the northern hemisphere caused by increasing air temperatures and enhanced precipitation in winter, causing an increase in soil temperature due to the insulating effect of the snow cover (Johansson et al., 2013; Dahlke et al., 2012). Both glaciers and permafrost have an influence on the hydrological cycle, especially on streamflow generation. Changes in the cryosphere therefore likely affect the hydrological cycle regionally at high latitudes. For example, studies on the shifts in minimum flows showed that the loss in permafrost influences a catchment’s hydrology. Specifically, it brings about higher infiltration rates and the thawing of ice in the ground that allows ground water recharge and increases in the annual minimum flow (Braberts & Walvoord, 2009).

Numerous studies have shown that extreme events linked to the hydrological system such as floods and droughts are changing due to climate change (e.g. Hall et al., 2014; Kundzewicz et al., 2014; Burn et al., 2010; Wilson et al., 2010). Burn et al. (2010) pointed out that changes in extreme events vary with location and catchment properties. They found changes towards decreasing annual maximum flows and trends towards earlier flood occurrence for snowmelt-dominated catchments across Canada. Cunderlik & Ouarda (2009) explored the magnitude and the timing of floods in Canada for both snowmelt and rainfall-dominated catchments and detected trends towards earlier flood occurrence and a decrease in flood magnitude for snowmelt-dominated catchments. Further, they saw an increasing number of catchments showing a bi-modal flow regime with two peaks in the annual hydrograph (one in late spring due to snowmelt and one in late summer due to rainfall events).

In terms of winter precipitation occurring as snow, there is clear evidence towards shorter snow duration and earlier snowmelt onset (e.g. Stewart et al., 2005; Cayan et al., 2001). Earlier snowmelt onset in western North America was linked to higher air temperatures, a loss of glaciers, less snow cover during winter and the influence of the Pacific Decadal Oscillation (PDO). The onset of snowmelt is often used as an indicator for a change in the flow regime, which characterizes a catchment’s hydrology. With the ongoing climate change, a shift from snowmelt to rainfall-dominated flow regimes is likely to happen in much of the Subarctic. This is typically represented by the later occurrence of the annual maximum flow caused by rainfall events instead of a peak located in late spring / early summer caused by snowmelt as is characteristic for snowmelt-dominated flow regimes (Cunderlik & Ouarda, 2009). Further, rainfall-dominated flow regimes are often characterized by a higher base flow (minimum flow during the dry period, which is during winter in northern Sweden) than snowmelt-dominated flow regimes.
Atmospheric circulation further plays an important role in a region’s flow regimes. Numerous studies in North America and Europe have linked hydroclimatic shifts to the atmospheric circulations over the Pacific and the Atlantic (e.g. Hannaford et al., 2013; Braberts & Walvoord, 2009; Woo & Thorne, 2008; Stewart et al., 2005). The hydrology in western North America is clearly linked to the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), as shown by Braberts & Walvoord (2009), who found a significant increase in winter streamflow during the warm PDO phase (phase of high air temperatures and low precipitation) in the Yukon basin (Canada) caused by increased groundwater discharge, earlier snowmelt in spring and greater snow accumulation. That study further pointed out the importance of the PDO on the timing of streamflow. The shift in PDO from its cold to its warm phase in 1976 was reported by numerous studies to be the driver for changes in streamflow (Braberts & Walvoord, 2009; Stewart et al., 2005). Woo & Thorne (2008) showed that the magnitude of flooding regional is sensitive to winter precipitation, whereas winter air temperatures influence the timing of streamflow. Eastern North America and Europe are influenced by the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). Evidence for the linkage of summer streamflow and the NAO index in the previous winter was found by Birsan et al. (2005) for Switzerland, whereas Sutton & Hodson (2005) could explain European summer climate with the fluctuations of the Atlantic’s sea surface temperatures (SST) associated with the AMO. Woo & Thorne (2008), Birsan et al. (2005) and Stewart et al. (2005) all referred to the complexity of the processes influencing the variability in streamflow and pointed out the importance of a catchment’s properties. Parameters such as storage, permafrost, and glaciers are changing continuously and the variability in streamflow cannot be described only through atmospheric variables.

Hall et al. (2014) summarized the literature on changes in flood magnitudes and occurrences across Europe and pointed out that for northern Europe, variable spatial and temporal patterns were detected. No indications for an overall pattern towards a change in flood regimes were detected. Note, this is in contrast to western Europe, where decreasing trends were found in Spain, for example (Mediero et al., 2014). This agrees with the study by Arheimer & Lindström (2015) who detected no trends in annual maximum flows or changes in flow regimes in Sweden. They showed that there is evidence for a change in the flow regime from snowmelt to rainfall-dominated systems, but focusing on the annual maximum flow, the second peak in late summer caused by rainfall events could not yet be detected. Unlike their study, Dahlke et al. (2012) found clear evidence of a decreasing trend in annual maximum flow for a catchment without glacier coverage and a clear increasing trend for a catchment with substantial glacier coverage in northern Sweden. From that study, the decreasing trend in peak flows for the catchment without glacier coverage was related to permafrost thawing bringing about increased storage and enhanced groundwater flow. Observed increasing trends in minimum flows across much of northern Sweden support these conclusions (Sjöberg et al., 2013). Wilson et al. (2010) found evidence for changes in streamflow in northern Europe, especially during winter and spring. They further concluded that trends in annual and seasonal streamflow, as well as trends in extreme events can be linked to precipitation and temperature trends, whereas the signal induced by temperature seems to be more clearly reflected in streamflow series. Lindström & Bergström (2004) found an increase in streamflow in northern Sweden. They attributed this to recent wet years and pointed out remarkable conditions with a combination of high air temperature and high precipitation causing floods. They further mentioned that extreme events increased more than
average streamflow and referred to the occurrence of high flow magnitudes in recent years (e.g. Sweden’s flood in 1995).

To this end, several studies linked the variability in streamflow in the Swedish Subarctic to large-scale atmospheric circulations such as the NAO and the East Atlantic (EA) pattern causing variability in air temperature and precipitation on different time scales (Hannaford et al., 2013; Dahlke et al., 2012). Hannaford et al. (2013) pointed out the difficulties arising interpreting trend analysis due to the decadal scale variability caused by atmospheric circulations such as the NAO.

1.2 Aim of this thesis

The aim of this thesis is to develop further knowledge on the generation of floods in the Swedish Subarctic by analyzing changes and linking variability in streamflow to climate. 18 catchments in northern Sweden were selected following the study from Sjöberg et al. (2013). Statistical analyses (after Dahlke et al., 2012) were applied on several important hydrological parameters to explore changes in the selected catchments. Trend analyses for the selected hydrological parameters were computed using the Mann-Kendall trend test. For all catchments, a flood frequency analysis was done fitting an extreme value type I distribution (also known as the Gumbel distribution) to the data. Stationarity of selected flood percentiles over time was tested using a moving window analysis. The results were compared to the results of the study by Sjöberg et al. (2013), who explored trends in minimum flows and were related to climatic conditions in the Swedish Subarctic.

The main interests of this thesis are:

- Are there changes in the hydrology of the selected catchments?
- Do the trends in high peak flows and minimum flows show similar patterns?
- What is the driving force of the high peak flow generation in the Swedish Subarctic?
Trends in high peak flow generation across the Swedish Subarctic

2 Methods

2.1 Site description

The catchments considered in this thesis (Figure 1) are based on the study of Sjöberg et al. (2013), which investigated trends in minimum streamflow to explore permafrost thawing in northern Sweden. One additional catchment was included, which the authors of Sjöberg et al. (2013) investigated, but not included in the final results. This particular catchment (Männikkö) was added since a long period of record was available. All 18 catchments considered in this thesis are unregulated and not highly impacted by humans. The catchments are located in northern Sweden at latitudes ranging from 65 and 69° N and cover most of the Swedish Subarctic. Many rivers in Sweden are regulated for hydropower purposes. Thus the catchments considered in the southern part of the study region are preferentially located in the west towards the Scandinavian mountain range, whereas the catchments in the northern part of the study region are spread out over the entire west-east span of the Swedish Subarctic, where the land is more pristine. The catchments considered have an area ranging from 100 to 10,000 km² and a mean elevation of 720 masl (Table 1).

The Swedish Subarctic is characterized by the Scandinavian mountain range in the west and the Baltic Sea in the east. The Scandinavian mountain range denotes the border to Norway and has elevations up to approximately 2100 masl in Sweden. The catchments considered in this thesis all drain towards the Baltic Sea, since the Scandinavian mountain range functions as the regional water divide.

Figure 1 Map over northern Sweden showing the location of the catchments considered.
The vegetation in the Swedish Subarctic is mainly birch forests, tall shrubs, meadow, heath and wetlands (Callaghan et al., 2013). These vegetation compositions are changing due to increasing air and soil temperatures and the thawing of permafrost. Especially an increase in tall shrubs and wetland graminoid vegetation was reported in recent years (Callaghan et al., 2010).

After the map of Brown et al. (1998), the catchments considered are located in the continuous, discontinuous, sporadic or isolated permafrost zone, depending on the catchment’s latitude and elevation (Christiansen et al., 2010). The three boreholes located in northern Sweden monitoring permafrost have shown an increase in active layer thickness in recent years (Romanovsky et al., 2010).

The glacial coverage in the catchments considered was estimated to be less than 2% of the catchments area (SMHI, 2013). The influence of glaciers is therefore likely negligible and not further considered in this thesis.

2.2 Climatic and hydrological conditions

The climate of the Swedish Subarctic is cold and humid. The catchments considered in this thesis show a mean annual air temperature between 0 and -8 °C with the lower values at higher elevations and latitudes. Precipitation varies on an east-west gradient with annual values up to 2000 mm/year in the west (mountainous areas) and 500 to 700 mm/year in the east. Mean annual air temperature and precipitation were estimated for the period 1961-1990 by the Swedish Meteorological and Hydrological Institute (SMHI, 2009a; SMHI, 2009b) (Figure 2).

Mean annual air temperature in Sweden is increasing in general and, over the last century, fluctuations have been present. Increasing values were measured in northern Sweden in the beginning of the 20th century until the early 1940s, followed by a decrease until the 1970s and an increase ever since to values higher than in the 1930s (Callaghan et al., 2010; Lindström & Alexandersson, 2004). The increase in air temperature is most pronounced in winter, whereas the temperature in summer did not rise significantly (Callaghan et al., 2013). Callaghan et al. (2010) further stated that winter extremes in air temperature are increasing, leading to enhanced snowmelt during winter, which agrees with the trend towards earlier snowmelt in the Swedish Subarctic detected by numerous studies (e.g. Hannaford et al., 2013; Callaghan et al., 2013; Wilson et al., 2010).

Mean annual precipitation has constantly increased over the last century in northern Sweden, as well as summer precipitation (Callaghan et al., 2010; Lindström & Alexandersson, 2004). Further, the variability of extreme precipitation events has increased since the beginning of the 20th century. Enhanced winter precipitation in the late 1980s and 1990s was reported by Holmlund et al. (2005). During winter, much of the precipitation falls as snow (Lindström & Bergström, 2004). Snow depth increased until the 1980s, but since then an accelerating decrease could be monitored (Callaghan et al., 2013). Also, snow duration decreased significantly over the last century (Arheimer & Lindström, 2015; Callaghan et al., 2013).
Streamflow in northern Sweden is mainly snowmelt-dominated, with peak streamflow occurring in late spring and summer (May to July) when about half the annual streamflow occurs (Lindström & Bergström, 2004). The spring flood in northern Sweden is approximately double the volume of the autumn flood, which is caused by rainfall events (Arheimer & Lindström, 2015). Lindström & Bergström (2004) investigated trends in streamflow in Sweden and detected a dry period in the 1970s followed by a wet period starting in the mid of the 1990s. They further detected a higher increase in extreme values than in average values over the entire 20th century starting in the 1990s with large floods both in 1995 and 2000. Especially the flood in 1995 was remarkable in northern Sweden, since it occurred in most catchments across the region. This flood was possibly caused by enhanced winter precipitation (Holmlund et al., 2005). Lindström & Bergström (2004) further pointed out that recent years were remarkable due to the combination of high temperatures and high streamflow. Wilson et al. (2010) explored annual and seasonal trends in the Nordic countries of Europe and found a notable increase in winter and spring flows, as well as in the annual streamflow for Sweden. They related the trends in streamflow to air temperature and precipitation and concluded that in the Swedish Subarctic, air temperature is more clearly reflected in streamflow records than precipitation. Studies focusing on low flows showed an increase in minimum flow due to an increase in precipitation (especially in winter) and the thawing of permafrost (Sjöberg et al., 2013). A loss in lake ice and a decrease in ice duration were reported over the last century, which could affect air temperature, vegetation and streamflow (Callaghan et al., 2013; Lindström & Bergström, 2004). The influence of ice jamming on the snowmelt flood in spring was mentioned by Lindström & Bergström (2004).
Climate in northern Sweden is generally influenced by large scale atmospheric circulations over the Atlantic Ocean. Sutton & Hodson (2005) showed that summer air temperatures in Europe are determined by the low-frequency variations of the Atlantic Multidecadal Oscillation (AMO). The AMO is driven by the Atlantic Ocean’s thermo-haline circulation and is expressed by a change in the sea surface temperature (SST) of the North Atlantic. Further, low precipitation in northern Europe can be related to a low-pressure anomaly located over the Atlantic Ocean (Sutton & Hodson, 2005). Hannaford et al. (2013) pointed out the importance of the North Atlantic Oscillation (NAO) on streamflow variability in Europe, especially in northern regions. That study further showed that the increase in streamflow after 1960 in northern Europe is linked to the positive phase of the NAO, which is characterized by above-average air temperatures, enhanced precipitation during winter and below-average summer precipitation. This agrees with the findings by Dahlke et al. (2012), who further pointed out the importance of the East Atlantic (EA) pattern on variability in streamflow causing above-average precipitation during winter in its positive phase.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC, 2013) predicted an increase in mean annual air temperature, mean annual precipitation and streamflow for the 21st century for the Swedish Subarctic compared to the period 1986 – 2005. Further, an increase in extreme events for both precipitation and streamflow has been predicted (Kundzewicz et al., 2014; IPCC, 2013). Arheimer & Lindström (2015) predicted a change in the flow regime for northern Sweden from snowmelt to rainfall-dominated. They further concluded that the flood magnitude is likely to decrease in the future due to earlier snowmelt and a lower peak in streamflow caused by snowmelt. In contrast, autumn and winter flows are likely to increase due to more intense precipitation events and less snow accumulation.

### 2.3 Data and hydrological parameters

The streamflow data used for this thesis (Table 1) is from the online database Vattenwebb (vattenwebb.smhi.se) of the Swedish Meteorological and Hydrological Institute (SMHI, 2013). For all catchments, daily streamflow measurements are available for at least 24 years (1990 – 2013). The total length of record for all the catchments varies between 24 and 103 years. Four catchments contain one or two data gaps, comprised of several years of missing data. Years with missing data were removed for the analyses. All analyses were done for the longest common period (1990 – 2013) and for the entire period of record available for each catchment. The last year considered for all catchments is 2013.

Due to the snowmelt-dominated hydrological regime in northern Sweden, which is characterized by a single peak in streamflow in late spring and early summer, all analyses are based on calendar years rather than hydrological years. The calendar year is commonly used for studies on streamflow in cold environments since it does not cut the wet period into two halves and each peak flow is associated with the correct year (e.g. Dahlke et al., 2012; Wilson et al., 2010; Birsan et al., 2005). The day of the year (DOY) in the analyses refers to the Julian calendar day. In the seasonal analysis, summer was defined as the months June, July and August (after Dahlke et al., 2012; Wilson et al., 2010; Birsan et al., 2005).

The hydrological parameters considered (Figure 3a) are the annual maximum streamflow, which represents the flood magnitude, and the date of the annual maximum streamflow, which represents the flood occurrence (Dahlke et al., 2012). Further, mean summer flow, date of the snowmelt onset and date of the center of mass were assessed.
Table 1 Properties for the catchments considered in this thesis. The label of the gauging station used by SMHI, the catchment area (km\(^2\)), the mean elevation of the catchment (masl), the elevation range (minimum and maximum elevation, masl), the first full year of record and the length of the record period (years) are listed. The length of the record period represents the entire length, whereas the numbers in brackets represent the number of years with actual data (years with missing data are subtracted). The last year considered for all catchments is 2013.

<table>
<thead>
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<th>Name</th>
<th>SMHI Label</th>
<th>Area (km(^2))</th>
<th>Mean elevation (masl)</th>
<th>Elevation range (masl)</th>
<th>Start year of the record</th>
<th>Length of the record period (years)</th>
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<td>580</td>
<td>205 - 1975</td>
<td>1968</td>
<td>46</td>
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<td>446 - 2081</td>
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<td>560</td>
<td>316 - 1505</td>
<td>1972</td>
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<td>2159</td>
<td>2351</td>
<td>795</td>
<td>473 - 2074</td>
<td>1976</td>
<td>38</td>
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<tr>
<td>Laisvall</td>
<td>2414</td>
<td>1534</td>
<td>825</td>
<td>429 - 1595</td>
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<tr>
<td>Lannavaara</td>
<td>5</td>
<td>3865</td>
<td>584</td>
<td>336 - 1346</td>
<td>1923</td>
<td>90 (60)</td>
</tr>
<tr>
<td>Männikkö</td>
<td>11</td>
<td>10038</td>
<td>551</td>
<td>207 - 1975</td>
<td>1915</td>
<td>98 (78)</td>
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<tr>
<td>Mertajärvi</td>
<td>1780</td>
<td>349</td>
<td>415</td>
<td>342 - 703</td>
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<tr>
<td>Niavve</td>
<td>591</td>
<td>1577</td>
<td>866</td>
<td>300 - 1991</td>
<td>1925</td>
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<td>Abiskojäkk</td>
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<td>969</td>
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<td>Skirknäs</td>
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<td>777</td>
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<td>783</td>
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<td>433 - 1862</td>
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<tr>
<td>Tängvattnet</td>
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<td>100</td>
<td>774</td>
<td>472 - 1365</td>
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<td>Tärendö 2</td>
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<td>7452</td>
<td>609</td>
<td>148 - 2086</td>
<td>1985</td>
<td>29</td>
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</tbody>
</table>

Snowmelt onset was determined after the algorithm for “spring pulse” onset of streamflow developed by Cayan et al. (2001). The spring pulse onset was calculated by subtracting the daily flow from the mean annual flow and accumulating these values by adding the value from the previous day. The first day where the value was larger than the previous day was identified as the day of spring pulse onset for these snowmelt-dominated catchments (Figure 3b). The snowmelt onset is a characterization of the shape of the hydrograph, and the flow regime of a catchment can be determined using this parameter (Stewart et al., 2005). Shifts in the flow regime can further be detected using snowmelt onset.

The center of mass indicates the day of the year, when the cumulative streamflow reached 50% of the total annual streamflow (Stewart et al., 2005). The center of mass is an indicator for the shape of the hydrograph and a shift in the flow regime can be detected calculating the center of mass (Whitfield, 2013). It has become a widely used indicator to relate snowmelt to climate variability and change. Whitfield (2013) pointed out that the center of mass as indicator for changes in the timing of the snowmelt caused by a change in temperature is only useful for pronounced hydrological regimes such as those associated with snowmelt-dominated regimes.
The date of the center of mass \((CT)\) was calculated using the following equation (modified after Stewart et al., 2005):

\[
CT = \frac{\sum(t_iq_i)}{\sum q_i}
\]  

(1)

where \(t_i\) is the day of the year and \(q_i\) is the corresponding streamflow at the same day of the year.

Stewart et al. (2005) pointed out that both the approaches for snowmelt onset and center of mass should be addressed to detect evident changes in the actual melting. This highlights that a change only in spring pulse onset or center of mass does not compulsory show a change in the flow regime caused by a change in temperature.

All the parameters mentioned describe a catchment’s hydrology. A shift in the hydrological regime and a change in the hydrology of a catchment caused by climate change or a shift in the catchment properties (e.g. thawing permafrost or melting glaciers) can potentially be detected by exploring trends in these parameters. This has been shown in numerous studies computing climate change impacts on hydrology through trend analyses on streamflow (e.g. Dahlke et al., 2012; Wilson et al., 2010; Stewart et al., 2005; Cayan et al., 2001).

For this thesis, all subsequent analyses were computed using Matlab (Version MATLAB R2013a) and R (Version 3.1.0). The annual maximum flow (flood magnitude) is a measure for changes in flood percentiles and further used for the flood frequency analysis (see following sections).

![Figure 3 a) Annual hydrograph for the Övre Abiskojákk catchment in the year 2000 with the hydrological parameters marked explored in this thesis. The flood magnitude represents the annual maximum flow and the flood occurrence the date of the annual maximum flow. DOY is the day of the year based on the calendar year (modified after Stewart et al., 2005). b) Visualization of the calculation for the spring pulse of snowmelt onset. The pulse day is defined as day when the cumulative streamflow starts increasing (modified after Cayan et al., 2001).](image)
2.4 Statistical analyses

2.4.1 Trend statistics

The time series of the hydrological parameters mentioned were tested for changes over time using a trend test. Analyzing trends is a common approach to determine whether there are changes in a system and what the drivers are - especially in hydrology (Hannaford et al., 2013). Time series were assumed to show no serial correlation. Clarke (2013) showed that this assumption is justifiable when exploring time series of the annual maximum flow. This is because one year is represented by one value. Trends were tested for significance for each catchment. Cross-correlation between the catchments was not taken into account, since all catchments were analyzed separately (Clarke et al., 2013; Douglas et al., 2000).

Trends in the various time series were investigated using the Mann – Kendall trend test (Yue et al., 2002; Douglas et al., 2000; Helsel & Hirsch, 2002). This is a powerful and widely used trend test for hydro-meteorological purposes (e.g. Hannaford et al., 2013; Sjöberg et al., 2013; Dahlke et al., 2012; Cunderlik & Ouarda, 2009). The Mann – Kendall trend test is a rank-based, nonparametric test based on the assumption that there is no serial correlation. The test determines whether a time series show a significant trend without specifying whether this trend is monotonic or not (Helsel & Hirsch, 2002). The Mann-Kendall trend statistics (Kendall’s $S$) is based on the following statistic (after Yue et al., 2002):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$

(2)

where $x_i$ are the data series values, $n$ is the length of the data set and

$$\text{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}$$

(3)

where $\theta$ represents $(x_j - x_i)$.

For the case $n \geq 8$ and to account for ties, the statistic $S$ is corrected and approximately normal distributed when the mean $E(S) = 0$ and the variance $V(S)$ is:

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i (i-1)(2i+5)}{18}$$

(4)

where $t_i$ is the number of ties of extend $i$ and $n$ is the number of values.

From this, the standardized test statistic $Z$ is computed by

$$Z_{MK} \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases}$$

(5)

The output of the Mann-Kendall trend test is a 2-sided $p$-value which indicates whether a trend is significant at a chosen level. Trends for each catchment were calculated for the entire period of record as well as for the common period 1990 – 2013. Trends in flood magnitude, flood occurrence, mean summer flow, date of the snowmelt onset and date of the center of mass were assessed. All trends were computed at a 95% confidence interval, which is a common level used
for trend analyses (e.g. Sjöberg et al., 2013; Dahlke et al., 2012; Burn et al., 2010; Cunderlik & Ouarda, 2009; Cayan et al., 2001).

To determine the linear rate of change over one decade, the slope of a linear regression line was fit to the data (Dahlke et al., 2012). The linear regression line is based on the linear equation \( y = ax + b \) where \( a \) is the slope of the regression line, \( b \) is the intercept, \( x \) is the year and \( y \) is the streamflow (\( \text{m}^3/\text{s} \)) or DOY, depending on the data considered. To be able to compare the linear rate of change of the catchments, relative changes in percent were calculated for annual maximum flows and mean summer flows. The linear rate of change is easier to interpret than the \( p \)-value computed with the Mann-Kendall trend test and used to be able to compare the catchments.

### 2.4.2 Flood frequency analysis

To assess the frequency of a flood, which is represented by the return period (in years) and the exceedance probability, an extreme value type I distribution (also known as the Gumbel distribution) was fit to all annual flood peaks of the catchment. For this, each time series was first sorted in ascending order after the observed annual maximum flow. The method of moments was used to estimate the parameters of the Gumbel distribution. The method of moments is based on the mean, the variance and the standard deviation of a data set and therefore a quick and simple method to estimate the parameters of a distribution (Loucks et al., 2005; Vogel, 1987).

The Gumbel distribution has the cumulative distribution function \( F_X(x) \) (Loucks et al., 2005):

\[
F_X(x) = \exp \left\{ - \exp \left( - \frac{x - \xi}{\alpha} \right) \right\}
\]

where \( X \) is a random variable, \( x \) is a possible value of \( X \), \( \xi \) is the location parameter and \( \alpha \) is the scale parameter. The location parameter \( \xi \) and the scale parameter \( \alpha \) are calculated using

\[
\mu_X = \xi + 0.5772 \alpha
\]

\[
\sigma_X^2 = \pi^2 \alpha^2 / 6
\]

where \( \mu_X \) is the mean and \( \sigma_X^2 \) the variance of the data set.

Model adequacy of the fitted Gumbel distribution was tested using different techniques. A graphical check was done plotting the quantiles of the fitted Gumbel distribution \( \left( G^{-1}\left( (i-0.44)/(n+0.12) \right) \right) \) versus the observations \( X_{(i)} \). Gringorten’s plotting position \( (i-0.44)/(n+0.12) \), where \( i \) is the rank of the ordered observed values \( X_{(i)} \) and \( n \) is the length of the time series) was applied, which is recommended for the Gumbel distribution, since it is optimized for the largest observation (Stedinger et al., 1993; Vogel, 1987). Further, model adequacy was tested applying the Kolmogorov-Smirnov test for goodness-of-fit. This test provides bounds within all observations should fall if the fit of the distribution is appropriate (Chowdhury et al., 1991). The test specifies that

\[
\Pr \left[ F^{-1} \left( \frac{i}{n} - K_{\theta} \right) \leq y_{(i)} \leq F^{-1} \left( \frac{i-1}{n} + K_{\theta} \right) \right] = 1 - \theta
\]

where \( y_{(i)} \) are the ordered values of a sample size \( n \) with \( y_{(i)} \leq \ldots \leq y_{(i)} \leq \ldots \leq y_{(n)} \) \( \Pr \) \[ \] is the probability of the argument inside the brackets, \( F^{-1} \) represents the inverse of the fitted Gumbel distribution and \( K_{\theta} \) is the critical value at significance level \( \theta \).
The critical level $K_\theta$ was computed after Chowdhury et al. (1991):

$$K_\theta = \frac{\bar{\omega}_1}{n^{0.5}} - \frac{\bar{\omega}_2}{n^2}$$  \hspace{1cm} (10)

where $\omega$ are given in Table 1 in Appendix A and $n$ is the sample size.

The values for $\tau_2$ are regional values estimated using $L$-moments (Loucks et al., 2005). $L$-moments are an alternative description of the statistical properties of a probability distribution and were preferred over the method of moments for goodness-of-fit tests, since they are linear functions of the data and easy to compute (Loucks et al., 2005; Chowdhury et al., 1991). $L$-moments can be calculated using probability weighted moments (PWM). The first and the second $L$-moment were used for this thesis. The first $L$-moment ($\beta_1$) is simply the sample mean. The second $L$-moment $\lambda_2$ is calculated using

$$\lambda_2 = 2 \beta_1 - \beta_0,$$

where $\beta_i$ is defined as the second probability weighted moment (after Loucks et al., 2005):

$$\beta_1 = \frac{1}{n(n-1)} \sum_{j=2}^{n} (j-1) X(j)$$  \hspace{1cm} (11)

where $n$ is the sample size, $j$ is the rank starting at the second position (second value has rank one) and $X$ is the observed value.

The regional $\kappa$ for the Gumbel distribution is zero. This parameter is equivalent to the coefficient of skewness, which describes the upper tail of the distribution. The extreme value distribution is reduced to the Gumbel distribution applying the coefficient of skewness $\kappa = 0$ (Chowdhury et al., 1991). The Kolmogorov-Smirnov bounds were calculated at a significance level $\theta = 0.05$. A higher significance level (e.g. $\theta = 0.01$) provides wider bounds and the distribution therefore is more likely to show a good fit.

The goodness-of-fit was further tested applying Filliben’s Probability Plot Correlation Coefficient (PPCC) test on the fitted Gumbel distribution (Loucks et al., 2005; Chowdhury et al., 1991; Vogel, 1987). The PPCC test is a commonly used and powerful goodness-of-fit test based on statistics instead of graphics (Loucks et al., 2005). It assesses the correlation between the ordered observations and the corresponding fitted quantiles of the distribution and therefore measures the linearity of a probability plot (Chowdhury et al., 1991). The fitted quantiles are based on Gringorten’s plotting position. The PPCC test was calculated after Loucks et al. (2005):

$$r = \frac{\sum_{i=1}^{n} (x(i) - \bar{x})(w_i - \bar{w})}{\left[\sum_{i=1}^{n} (x(i) - \bar{x})^2 \sum_{i=1}^{n} (w_i - \bar{w})^2\right]^{1/2}}$$  \hspace{1cm} (12)

where $x(i)$ are the ordered observations, $\bar{x}$ is the mean of the observations, $w_i$ are the fitted quantiles defined as $w_i = G^{-1}(p_i)$ for plotting position $p_i$ for each $x(i)$ and $\bar{w}$ is the mean of the fitted quantiles.

The $r$ – value provides a quantitative measurement of the goodness-of-fit of the distribution. Lower critical values for the PPCC test are given in Table 2 in Appendix A (after Loucks et al., 2005).

Return periods and exceedance probabilities can easily be calculated using the parameters from the Gumbel distribution. The value $x$ with a probability of occurrence $p$ can be obtained using:

$$x_p = \xi - \alpha \ln[-\ln(p)]$$  \hspace{1cm} (13)

where $\xi$ is the location parameter, $\alpha$ is the scale parameter and $p$ is the probability (after Stedinger et al., 1993).
Floods are more often referred to using the return period, which can be converted from \( p \) using
\[
p = 1 - \frac{1}{T},
\]
where \( p \) is the probability and \( T \) is the corresponding return period in years.

To explore changes in the flood percentiles, an additional analysis was done. Stationarity of selected flood percentiles was tested using 10-yr moving windows. The 50th, 90th, 95th, 98th and 99th percentiles were selected after Dahlke et al. (2012). The percentiles correspond to a flood with a return period of 2, 10, 20, 50 and 100 years, respectively. The 2-year flood represents the median flow and was not further considered as flood interpreting the results (Loucks et al., 2005). For each window, a Gumbel distribution was fit to all flood peaks within the window and the goodness-of-fit of the fitted distribution was tested with the PPCC test as explained above.

Finally, trends in each flood percentiles over time were estimated fitting a generalized least square regression model using a maximum likelihood estimator (Dahlke et al., 2012; Fox, 2002). To be able to account for serial autocorrelation in the errors of the time series, an ordinary least square (OLS) regression was preliminarily fit to the data. The residuals of the OLS, the autocorrelation function (ACF) and the partial autocorrelation function were then calculated and plotted. The order of the autoregression process was determined using the ACF and the partial ACF. A sinusoidal decay in the partial ACF with a positive first and a negative second spike, as detected for the time series, is indicative for a second order autoregression, or AR(2), process (Fox, 2002).

Serial autocorrelation in the errors of the time series were determined applying the Durbin-Watson test on the OLS regression model (Fox, 2002; Fox & Hartnagel, 1979). This test quantifies the serial autocorrelation in the time series based on the residuals. Fox (2002) preferred the Durbin-Watson test over the lag-residual autocorrelation due to the distribution of the residuals, which is not independent. The Durbin-Watson statistics

\[
D_s = \frac{\sum_{t=s+1}^{n} (e_t - e_{t-s})^2}{\sum_{t=1}^{n} e_t^2}
\]

where \( n \) is the length of the time series, \( t \) is the time (or for this thesis the corresponding year), \( s \) is the lag of the residual and \( e_t \) is the residual at time \( t \).

After specifying the correlation structure, the generalized least square (GLS) estimation technique was applied as suggested in Fox & Hartnagel (1979) for significantly autocorrelated errors in the time series. The GLS regression model was preferred over the OLS due to the more accurate estimates of the regression parameters and standard errors. An autoregressive moving average model (ARMA(2,0) structure) was fit to the errors in the residuals of the GLS model to account for autocorrelation in the residuals of the moving windows. The ARMA(2,0) structure specifies that only a second order autoregression process was fit to the data. The order of the AR process was determined using the partial ACF as mentioned above. The moving average (MA) component, specified by \( q = 0 \), is absent. This was applied because the differences in the maximum likelihood estimates of the regression parameters under AR(2) error correlation (with GLS) were similar to the OLS estimates (Fox, 2002). The output of the GLS model is a \( p \)-value which describes whether there is a significant trend in the time series. A significance level of 0.05 was applied to determine the stationarity of the tested flood percentile.
3 Results

3.1 Trend analyses

Linear rates of changes over one decade were determined for different hydrological parameters (Table 2). A decreasing trend is represented by a negative linear rate of change, whereas a positive linear rate of change corresponds to an increasing trend. A decreasing trend represents a lower flow for annual maximum and mean summer flows and earlier in the year in terms of the DOY. In general, it is notable that for most of the analyses just a few catchments showed significant trends. Only the analysis on the mean summer flow over the common period and the analysis on the onset of snowmelt showed significant trends for about half of the catchments considered (ten and eight catchments, respectively). It has to be mentioned at this point that interpreting the results of these trend analyses are linked to uncertainties, which are discussed later on in this thesis.

Looking at the annual maximum flow, which represents the flood magnitude, only one catchment (Stenudden, \( p = 0.02 \), Figure 4a) showed a significant (decreasing) trend over the entire period of record. There were both increasing and decreasing trends for the annual maximum flow across the other catchments, but not significant. The linear rate of change over one decade ranged from -7.4 to +4.3%. Over the common period 1990 – 2013 no significant trends in annual maximum flow were detected. There were both increasing and decreasing trends at non-significant levels. The linear rate of change varied between -10.4 and +12.4%. It is interesting that most of the catchments showed one or more large floods (high values for annual maximum flow which are associated with high return periods in the flood frequency analysis) in the recent two decades (years 1995, 2004, 2005, 2012). Especially the year 1995 showed a higher annual maximum flow for nine catchments. The Stenudden and Gautrask catchments are shown as examples in Figure 4. It is clearly visible, that these two catchments experienced a large flood in 1995. For the Stenudden catchment, a long record period of continuous measurements is available which showed high flows in the 1920s. The Gautrask catchment showed an increasing trend at non-significant level with remarkable high flows in the years 1995, 2005, 2010 and 2013.

Over the entire period of record, the date of the annual maximum flow, which is measured as day of the year (DOY) and represents the flood occurrence, showed a significant decreasing trend for two catchments (Laisvall, \( p = 0.03 \) and Solberg, \( p = 0.04 \)). A decreasing trend represents an earlier flood occurrence. The median date of the annual flood was June 14 (DOY = 165) and June 6 (DOY = 157) for the Laisvall and the Solberg catchments, respectively. For almost all catchments a decreasing trend was detected (exceptions: Abisko, \( p = 0.96 \) and Mertajärvi, \( p = 0.75 \)), but not at significant levels. Catchments with a decreasing trend in the date of the annual maximum flow, showed a rate of change over one decade varying from 0.3 to 7.7 days. The catchments which showed an increasing trend (later flood occurrence) had a linear rate of change over one decade of 0.5 and 2.6 days for the Abisko and Mertajärvi catchments, respectively. Considering all catchments, the median date of the annual flood was in June (DOY = 149 to 181) with ranges from the beginning of May (DOY = 120) to the beginning of October (DOY = 283). Over the common period, a significant (decreasing) trend in flood occurrence was detected for three catchments (Karesuvanto, \( p = 0.03 \), Laisvall, \( p = 0.03 \) and Stenudden, \( p = 0.01 \)). Almost all catchments showed decreasing trends in flood occurrence (exceptions are Karats, \( p = 0.49 \) and Mertajärvi, \( p = 0.84 \)). The linear rate of change was 1.6 to 10.6 days per decade for the catchments with earlier flood occurrence and 6.7 and 14.0 days per decade for the Karats and Mertajärvi catchments, respectively, which showed a later flood occurrence. The median date of the annual
flood was in June (DOY = 148 to 182) with ranges from the beginning of May (DOY = 120) to the beginning of October (DOY = 283).

The results of the analysis on the mean summer flow showed the clearest picture. Over the common period, all catchments experienced decreasing trends for mean summer flows. Ten catchments showed a significant decreasing trend. The linear rate of change ranged from 6.6 to 26.3% less mean summer flow. Six catchments showed a decrease in mean summer flow of more than 20% over one decade. Two catchments (Laisvall, $p = 0.01$ and Övre Abiskojäkk, $p = 0.01$) further showed a significant decreasing trend in the mean summer flow over the entire period of record. The Övre Abiskojäkk catchment is shown in Figure 5 as it exemplifies the region. For the other catchments, both increasing and decreasing trends at non-significant levels were detected. The linear rate of change over the entire period ranged from a decrease in mean summer flow of 22.5% to an increase of 3.8%. Higher changes in mean summer flow were detected for the catchments showing a decreasing trend.

The trend analysis on the snowmelt onset date also showed a clear picture. Decreasing trends were detected for most of the catchments over the entire period (exception Tärendö 2, $p = 0.56$), with significant trends for eight catchments. The linear rate of change over one decade was 0.2 to 4.8 days for catchments with earlier onset of snowmelt. Tärendö 2, the only catchment with a positive trend towards later onset of snowmelt showed a linear rate of change over one decade of 1.6 days. The Övre Abiskojäkk catchment is shown as example in Figure 6. Two catchments (Abisko, $p = 0.03$ and Övre Abiskojäkk, $p = 0.02$) showed a significant decreasing trend in the date of snowmelt onset over the common period. Decreasing trends were detected for almost all catchments (exceptions Männikkö, $p = 0.80$ and Tärendö 2, $p = 0.43$). The linear rate of change varied from 0.4 to 7.4 days per decade for catchments with earlier snowmelt onset and 0.8 to 2.3 days per decade for positive trends.

The results of the analysis on the center of mass were not as clear as the others. The change in the date of the center of mass over the entire period of record was only significant for one
Trends in high peak flow generation across the Swedish Subarctic catchment (Stenudden, $p = 0.02$). The non-significant trends showed both increasing and decreasing trends. The linear rate of change varied from 0.005 to 1.5 days for the catchment with trends towards earlier center of mass and 0.1 to 1.9 days for catchments with positive trends towards a later center of mass. Over the common period of record, no significant trends were detected for the change in date of the center of mass. Both increasing and decreasing trends at non-significant levels were observed, where increasing trends were in the majority. The linear rate of change over the common period was less than one day per decade for an earlier and 0.2 to 5.3 days per decade for a later center of mass. It is interesting that over the entire period of record, both decreasing and increasing trends were detected, which mostly changed to positive trends over the common period of record (exceptions are the Abisko, Laisvall and Lannavaara catchments, which showed a negative trend over both the entire and the common period of record).

Exploring the trends of all analyses, no consistency was found. It is interesting that the Stenudden catchment showed a significant trend for all the analyses. This is a catchment with a long period of continuous measurements (98 years) and can therefore be considered as a good indicator for changes in the system over the past century. Three catchments (Kaalasjärvi, Lannavaara and Tärendö 2) showed non-significant trends for all analyses. It can further be pointed out that the period of record is important interpreting the results from trend analyses. There are differences in the number of catchments showing significant trends when comparing the entire and the common period for each analysis.

![Figure 5 Trend analysis on the mean summer flow (June to August, in m$^3$/s) for the Övre Abiskojákk catchment. The solid line represents the linear trend over the entire period of record, whereas the dashed line represents the linear trend over the common period 1990-2013. The $p$-value represents the 2-sided $p$-value computed with the Mann-Kendall trend test.](image-url)
Flood magnitude and mean summer flow for Tärendö 2.

**Table 2** Linear change rates applying a trend analysis over the entire (left side) and the common (right side) period of record. Linear rates of change over one decade determined with a linear regression line are shown. Relative changes (%) are shown for flood magnitude and mean summer flows. Changes in flood occurrence, snowmelt onset and center of mass are in days. Trends computed with the Mann-Kendall trend test significant at a level of 5% are highlighted in bold. A negative linear rate of change corresponds to a decreasing trend and a positive rate of change corresponds to an increasing trend.

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<td>Flood magnitude (%)</td>
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<td>2.6</td>
</tr>
<tr>
<td>Niavve</td>
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<td>-1.1</td>
</tr>
<tr>
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</tr>
<tr>
<td>Skirknäs</td>
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<td>-0.4</td>
</tr>
<tr>
<td>Solberg</td>
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<td>-1.5</td>
</tr>
<tr>
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<td>-0.4</td>
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<tr>
<td>Tängvattnet</td>
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<td>-1.5</td>
</tr>
<tr>
<td>Tärendö 2</td>
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<td>-0.4</td>
</tr>
</tbody>
</table>

**Figure 6** Trend analysis on the date of the snowmelt onset (day of the year, DOY, based on calendar years) for the Övre Abiskojäkk catchment. The solid line represents the linear trend over the entire period of record, whereas the dashed line represents the linear trend over the common period 1990-2013. The p-value represents the 2-sided p-value computed with the Mann-Kendall trend test.
3.2 Comparison of annual minimum and maximum flows

Trends in the annual maximum flows were further compared to trends in the annual minimum flows computed by Sjöberg et al. (2013) (Figure 7). Trends in the minimum flows were computed over the entire period of record. A different length of the record period was applied for the two analyses (see Table 2 in Sjöberg et al. (2013) for more information on the record period of the minimum flows), with differences both in the starting and ending years. Changes in minimum flows were computed using the linear rate of change over the entire period of record for each catchment.

Three catchments showed a decreasing trend in minimum flow (Övre Abiskojääkk, -3.0%, Kaalasjärvi, -0.2% and Niavve, -0.2%). The Övre Abiskojääkk catchment was the only catchment showing a significant decreasing trend (at 5% significance level). A significant increasing trend in minimum flow was detected for nine catchments. The changes in minimum flow were smaller (-3.0 to +3.9%), even though linear rates of change were calculated over the entire period of record. Considering the maximum flows over the entire period, the Stenudden catchment was the only catchment showing a significant (decreasing) trend. The linear rate of change over one decade for the Stenudden catchment was -2.5%. The trends in annual maximum flows were more diverse with seven increasing and ten decreasing trends at non-significant levels. Considering all catchments, the changes in maximum flows were larger, although calculated as linear rate of change over one decade, ranging from -7.4 to +4.3%.

The Stenudden catchment showed a significant trend for both the annual minimum and maximum flows. What is conspicuous here is the slope of the trend. Whereas a significant increase in minimum flow was detected, there was a significant decreasing trend detected for the annual maximum flow. In general it is interesting that only five catchments (Gauträsk, Junosuando, Solberg, Tängvatnet and Tärendö 2) showed the same slope of the trend for both annual minimum and maximum flows.

![Figure 7](image-url) **Figure 7** Comparison of the linear change rate for the annual minimum (% change over the entire period of record) and annual maximum flows (% change over one decade). Red dots represent significant trends (at 95% confidence level) for the annual minimum flow, blue dots with a red line represent significance for both annual minimum and maximum flows and black dots represent non-significant trends.
3.3 Flood frequency analysis

The annual maximum flow was further explored through a flood frequency analysis. This determines the return period of a certain flood event and the flood percentiles can be tested for stationarity. A flood frequency analysis further helps interpreting trends in annual maximum flows. The result of the flood frequency analysis is a probability plot after Vogel (1987). The probability plots of the Övre Abiskojåkk and the Gauträsk catchments are shown in Figure 8 as examples. The probability plots for all other catchments are shown in Appendix B. In each plot the three floods with the highest return periods are labeled. The flood with a return period of 2 years represents the 50th quantile (exceedance probability of 0.5), which is also known as the median flow. The probability plot clearly shows that most annual maximum flows are located around that value for a flood with a 2-yr return period. It is interesting that for both the Övre Abiskojåkk and the Gautträsk catchments the three floods with the highest return periods occurred in the last 20 years. In the Övre Abiskojåkk catchment, the flood in 2012 was estimated with a return period of more than 100 years and represents the largest flood that this catchment has experienced over the entire period of record (1986-2013). The Gautträsk catchment experienced three large floods within the last 20 years, whereas the floods in 1995 and 2005 were reported with return periods of more than 100 years and the 2010 flood of approximately 30 years. These catchments clearly showed an increase in extreme events in recent years. The result from the probability plot for the Gautträsk catchment is consistent with the result of the trend analysis on the annual maximum flows (Figure 4b).

The Gumbel distribution showed a good fit for all catchments. All observed values fell within the Kolmogorov-Smirnov bounds computed at a 95% confidence level. Further, the probability plot correlation coefficient test also showed a good fit. The lowest value resulting from this test was \( r = 0.959 \) for the Skirknäs catchment, which is above the lower critical value (Loucks et al., 2005) (Table 2 in Appendix A).

![Figure 8](image-url) Probability plots for a) the Övre Abiskojåkk and b) the Gautträsk catchments. Quantiles of the fitted Gumbel distribution using Gringorten’s plotting position are plotted against the observed values \( X_{(i)} \) (m³/s). The solid line represents the idealized Gumbel distribution and the dashed lines represent the Kolmogorov-Smirnov bounds at the 95% confidence level. Exceedance probabilities and return periods are plotted on the secondary x and y-axis, respectively. The three floods with the highest return periods are labeled.
Selected flood percentiles were further tested for stationarity over time using a moving window analysis with 10-yr windows. For each window, a Gumbel distribution was fit to the data and the goodness-of-fit was tested applying the probability plot correlation coefficient test after Vogel (1987). The minimum r-value for the PPCC test over the entire period of record was \( r = 0.735 \). This was accepted since the mean r-value over all windows was \( r = 0.914 \) for this particular catchment (Skirknäs). In total, three windows showed an r-value below the assumed threshold of \( r = 0.80 \). All the r-values were accepted however due to the mean r-values of \( r = 0.914 \) and \( r = 0.939 \) for these two particular catchments (Skirknäs and Solberg, respectively). Over the common period of record (1990 – 2013), the minimum r-value was \( r = 0.800 \) for the Karats catchment and all the results were accepted.

Analyzing the stationarity of selected flood percentiles, four catchments showed a significant trend over the entire period of record. A significant increasing trend for the 10, 20, 50 and 100-yr flood percentiles were detected for the Gauträs, Kaalasjärvi, Övre Abiskojäkk and Tängvatnet catchments. The Solberg catchment showed a significant increasing trend in the percentiles of the 10 and 20-yr floods (\( p = 0.03 \) and \( p = 0.05 \), respectively). There was a significant decreasing trend in the 2-yr flood percentile, which represents the median flow, for two catchments (Männikkö, \( p = 0.05 \) and Stenudden, \( p = 0.02 \)). Including all trends, there were both increasing and decreasing trends in the flood percentiles. There are catchments, where the slope of the trend line changed direction (e.g. Lannavaara) depending on the percentile considered. This behavior could only be detected for catchments without significant trends in their flood percentiles.

For the common period from 1990 – 2013, increasing trends for at least the 50 and the 100-yr flood percentiles were detected for three catchments (Gauträs, Övre Abiskojäkk and Tängvatnet). The Männikkö catchment showed a significant increasing trend for the 10 and the 20-yr flood percentiles, whereas a significant increase only in the 10-yr flood percentile was detected for the Junosuando catchment. Over the common period, three catchments showed a significant decreasing trend in the 10, 20, 50 and 100-yr flood percentiles. A significant increasing trend in the 2, 10 and 20-yr flood percentiles was detected for the Karats catchment. Additionally, the Skirknäs catchment (\( p = 0.01 \)) showed a significant decreasing trend in the 2-yr flood percentile.

One can see that there is consistency among the catchments showing a significant trend in the upper flood percentiles (50 and 100-yr floods) over the entire period of record (Gauträs, Övre Abiskojäkk and Tängvatnet). These catchments also showed a significant increasing trend over the common period. Exceptions are the Kaalasjärvi and the Solberg catchments. The former switched from a significant increasing to a significant decreasing trend for all the flood percentiles (no significance in the 2-yr flood). The latter showed a significant increase in the 10 and 20-year floods over the entire period and turned to a non-significant decreasing trend for all flood percentiles over the common period. Over the common period, there were catchments with significant trends for flood percentiles that were not significant for the entire period of record. The Junosuando catchment, for example, turned significant for the trend of the 10-yr flood percentile and the Männikkö catchment for the 10 and the 20-yr flood percentiles. Significant decreasing trends in all the flood percentiles were detected for two catchments (Abisko and Stenudden). The Karats catchment showed a significant decreasing trend in the lower flood percentiles (2 to 20-yr floods) and a significant decreasing trend in the median flow (2-yr flood) was detected for the Skirknäs catchment.
Table 3: Trends and stationarity of selected flood percentiles over both the entire period (left side) and the common period (right part). A moving window analysis with 10-year windows was computed and stationarity was assessed by fitting a least-squares regression model. Values that indicate stationarity are shown. A moving window analysis with 10-year windows was performed for the entire period.

<table>
<thead>
<tr>
<th>Station</th>
<th>Common period 1990-2013</th>
<th>Entire Period</th>
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<tbody>
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<td>Tärendö</td>
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<td>0.92</td>
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</table>

100 years respectively, and an annual exceedance probability of 0.5, 0.05, and 0.1 respectively. The second flood percentile are the 50th, 95th and 99th percentiles, which correspond to a flood with a return period of 2, 10, 20, 50, and 100 years respectively. The second flood percentiles are the 50th, 95th and 99th percentiles, which correspond to a flood with a return period of 2, 10, 20, 50, and 100 years respectively.
Trends in high peak flow generation across the Swedish Subarctic

Considering the median flow, which is represented by the 2-yr flood, the results of the flood frequency analysis agree with the results of the trend analysis on the flood magnitude. The median flow showed both increasing and decreasing trends at non-significant levels, whereas all significant trends were decreasing, indicating changes towards lower flows. The Stenudden catchment, which was the only catchment with a significant trend for the flood magnitude \( p = 0.02 \), Figure 4a, showed a significant decrease in the 2-yr flood over both the entire and the common period \( p = 0.02 \) and \( p < 0.01 \), respectively.

The Övre Abiskojåkk catchment (Figures 9a and 9b) showed a significant increasing trend in the 10, 20, 50 and 100-year flood quantiles. The result from the moving window analysis is consistent with the probability plot (Figure 8a) which showed that the largest flood measured occurred in the year 2012. In the time series of the Stenudden catchment (Figures 9c and 9d), the two wet periods mentioned by Lindström & Bergström (2004) are clearly visible. The long period of record available shows the flood in 1922 as a first peak in the flood percentiles and the one in 1995 as the second peak in the flood percentiles with the dry period in the 1970s between. Over the common period, the 1995 flood is clearly visible in the beginning, since it was the only large flood in recent years. The Tångvattnet catchment (Figures 9e and 9f) showed a significant increase in the flood quantiles of the 20, 50 and 100 year floods (over the entire period (left graph) also in the 10-year percentile), which is consistent with the results from the flood frequency analysis, which showed that this catchment experienced the three largest floods in recent years (2005, 1995 and 2011, as shown in Appendix B). The median flow stayed approximately on the same value over the entire period of record for the Övre Abiskojåkk and the Tångvattnet catchments, whereas the Stenudden catchment showed a significant decrease in the 2-year flood percentile over both the entire and the common periods.
Figure 9 Trends in the floods with a return period of 2, 10, 20 and 100 years (50th, 90th, 95th, 99th percentiles) over the entire period of record (left graphs) and the common period 1990-2013 (right graphs). Trends were estimated fitting a generalized least square regression model using a 10-yr moving window. The solid lines represent the linear trends in the flood percentiles and the dashed lines represent the percentile estimates over the entire period of record. The 100-yr flood is marked in red, the 20-yr flood in green, the 10-yr flood in blue and the 2-yr flood (median flow) in black. The Övre Abiskojákk (a,b), Stenudden (c,d) and Tängvatnet (e,f) catchments are shown as they exemplify the region.
4 Discussion

4.1 Changes in hydrology and shift in flow regime

The results (Table 2) showed significant trends only for a few catchments, whereas there were differences in the results of the parameters explored. Both increasing and decreasing trends at non-significant levels were detected for all trend analyses. Consistency was found for the catchments showing a significant trend, which all showed a negative slope indicating lower flows (for the flood magnitude and the mean summer flow) and earlier timing for flood occurrence, snowmelt onset and center of mass. The diversity in trends (both for the slope and the significance) is consistent with studies on trends in northern Europe, which detected high variability in trends at a regional scale, showing that there are likely processes going on locally influencing the hydrology (Hall et al., 2014; Wilson et al., 2010; Burn et al., 2010).

Nevertheless, the results of the trend analyses showed that there are changes going on in the Swedish Subarctic at a catchment scale, although not all hydrological parameters showed significant trends. This is consistent with the study of Wilson et al. (2010), who investigated changes in streamflow in northern Europe and pointed out that there is regional variability in the trends. The length of the record period further has a high impact on the result of a trend analysis, as shown by Hannaford et al. (2013). This study concluded that, especially to be able to link trends in streamflow to multi-decadal climate fluctuations caused by atmospheric circulations, long record periods should be investigated on trends and a multi-temporal approach should be applied. The variability in streamflow mentioned by Lindström & Bergström (2004) is visible in the results of the annual maximum flow of the Stenudden catchment, which contained a long period of record starting in 1916. This catchment (Figure 4a) showed a wet period with high annual maximum flows in the 1920s and starting in the 1990s again, whereas in the 1950 and 1960s the annual maximum flow showed lower flows. Both the increasing and decreasing trends in flood magnitude at non-significant levels could possibly indicate differences in the development of the regime shift as a function of the catchment’s size, location, topography, elevation and state of permafrost (Dahlke et al., 2012; Woo & Thorne, 2008; Birsan et al., 2005). Especially the degradation of permafrost can dampen the shape of the hydrograph by reducing the flood magnitude due to an increased water uptake in the ground, which was detected in the Swedish Subarctic (Dahlke et al., 2012).

Further, several catchments contain a substantial area covered with inland water bodies such as lakes. As mentioned in Callaghan et al. (2013), ice break up was occurring earlier in recent years due to increasing winter air temperatures and enhanced streamflow. This further alters the streamflow peak during snowmelt explaining the decreasing trends in flood magnitude (Woo & Thorne, 2008). The wet period mentioned in Lindström & Bergström (2004) showed an increase in floods since the 1990s. High flood magnitudes were detected for most of the catchments in the years 1995, 2004/2005 and 2011/2012/2013 (Figures 4b and 8). Holmlund et al. (2005) reported enhanced winter precipitation during the late 1980s and 1990s, which is possibly the driver of the remarkable flood in 1995 occurring in most of the Swedish Subarctic. The absence of a significant trend in the flood magnitude could be due to the increase in floods in recent years for some of the catchments considered, which influenced the slope of the trend. The absence of an overall pattern in trends for the analyses on the flood magnitude and flood occurrence agrees with other studies on streamflow in northern Sweden, which found no consistent trends in these parameters (Arheimer & Lindström, 2015; Hall et al., 2014; Hannaford et al., 2013; Wilson et al., 2010).
Comparing the outcome from the study by Dahlke et al. (2012) for the Abisko catchment (corresponds to the Övre Abiskojåkk catchment considered in this thesis) with the results of this thesis, the influence of recent flood years and the sensitivity of trends to the record period can be shown. A longer period of record (1919-2009) was considered by Dahlke et al. (2012), which showed the wet period in the 1920s. The common period in that study was 1985-2009. This thesis applied the entire period 1986-2013 and the common period 1990-2013 for the Övre Abiskojåkk catchment. The trends observed by Dahlke et al. (2012) could be corroborated for mean summer flows and flood occurrence. The former showed a significant decreasing trend over the entire and the common period in this thesis (Figure 5) and over the common period by Dahlke et al. (2012). For the latter decreasing trends at non-significant levels were detected for all periods except the entire period in Dahlke et al. (2012), which showed a significant decreasing trend. The flood magnitude showed a non-significant decreasing trend for both the entire and the common periods in Dahlke et al. (2012), whereas this thesis detected increasing trends at non-significant levels for both periods of record.

This change in the slope of the trend, especially for the common period, is mainly due to the flood in the year 2012, which showed a return period of more than 100 years (based on the record period 1986-2013) (Figure 8a). The differences in the length of the record therefore clearly influenced the results of the flood frequency analysis. The largest flood recorded in 1939 (return period of more than 200 years based on the record period 1919-2009) was not in the record for this thesis. The trends were consistent for both studies and their particular largest floods. An increasing trend was detected for the time series showing the highest flow in the end of the record period, whereas a decreasing trend was found for the time series with the highest flow in the beginning of the record period. Nevertheless, the interpretation of the trend computed in this thesis has to be used with caution. The trend computed for this thesis was not significant ($p = 0.71$ and $p = 0.75$ for the entire and the common period, respectively). This example shows the impact of the record period chosen on the results of a trend analysis, as mentioned by Hannaford et al. (2013). Snowmelt onset and center of mass were not explored in Dahlke et al. (2012). Adding these two parameters to the analysis, a more accurate prediction for the shift in the flow regime could be done.

The results of the trend analyses indicate a shift in the flow regime in the Swedish Subarctic, as mentioned in the literature. Arheimer & Lindström (2015) found indications for a shift in the flow regime in Sweden from snowmelt to rainfall-dominated. Nevertheless they concluded that the shift has not yet been seen due to the differences in flood magnitudes. The spring flood caused by snowmelt is approximately twice the autumn flood caused by rainfall events in northern Sweden. That is consistent with the results of this thesis. Indications for a shift in the flow regime in the Swedish Subarctic were detected, as shown by the results in the flood magnitude, the flood occurrence and the snowmelt onset. For these parameters, all significant trends showed a negative slope indicating a decreasing flood magnitude, an earlier flood occurrence and an earlier snowmelt onset (Table 2). This is evident for a shift from the more pronounced snowmelt-dominated to the more dampened rainfall-dominated flow regime (Arheimer & Lindström, 2015). Due to the high snowmelt flood showing a decreasing trend and the increasing trend in autumn flood shown by Arheimer & Lindström (2015), a bi-modal flood regime is likely to develop, as suggested for Canada by Cunderlik & Ouarda (2009). To be able to prove the shift in flow regime, a seasonal analysis would have to be applied on the annual maximum flow to separate the floods in spring and autumn and to explore trends in the seasons separately (Stahl et al., 2010).
The mean summer flow showed the strongest trend towards lower flow, although Callaghan et al. (2013) showed that summer air temperatures stayed constant over the 20th century, while an increase in summer precipitation was observed. The decreasing trends of the mean summer flow are therefore likely to be driven by another parameter than climate. The accelerated degradation of permafrost and the thickening of the active layer shown by numerous studies in the Swedish Subarctic is likely to induce these changes in streamflow (e.g. Sjöberg et al., 2013; Callaghan et al., 2013; Dahlke et al., 2012; Åkerman & Johansson, 2008). The decrease in mean summer flow can be linked to the increase in active layer thickness causing an increase in subsurface flow due to enhanced thawing of ground ice, creating new flow paths in the ground, as shown by Dahlke et al. (2012). The trend in mean summer flow thus is another possible indicator for a shift in the regime, pointing towards a more equally distributed streamflow during the year and a dampening of the hydrograph. In contrast, Wilson et al. (2010) detected an increase in summer streamflow in northern Sweden for the period 1961-2000, whereas longer periods of record showed no trends in summer flows.

The center of mass analysis showed no clear patterns for the catchments considered. As mentioned in Whitfield et al. (2013), this approach is sensitive to minimum flows and precipitation during winter and more likely to indicate variations in the annual streamflow instead of a change in the timing of streamflow. The both increasing and decreasing non-significant trends found in this thesis support that hypothesis. Nevertheless, the center of mass can be used as indicator for a shift in the flow regime when connected to snowmelt onset and flood magnitude. Advanced shifts or changes in less pronounced flow regimes than the snowmelt-dominated regime can be detected assessing the center of mass. This is due to the interactions of processes causing the shift in flow regime, where the center of mass showed robustness. Therefore, to be able to apply the center of mass in the Subarctic, this approach has to be interconnected with other hydrological parameters. Analyzing the center of mass only, the absence of trends found by this thesis confirmed the weaknesses of this approach mentioned by Whitfield et al. (2013).

The trends in snowmelt onset are consistent with the outcomes from other studies, which found an earlier onset of snowmelt in North America, northern Europe and Switzerland (e.g. Callaghan et al., 2013; Braberts & Walvoord, 2009; Stewart et al., 2005; Birsan et al., 2005). This thesis showed a significant trend towards an earlier onset of snowmelt for approximately 50% of the catchments considered (Table 2), which is consistent with the increasing trends in precipitation and air temperature, showing an accelerated increase in the winter season (Callaghan et al., 2013). The onset of snowmelt is mostly driven by air temperatures in winter, influencing the timing of snowmelt, where above-average air temperatures lead to an earlier onset of snowmelt. This can further be linked to the flood magnitude in snowmelt-dominated catchments, as shown by Arheimer & Lindström (2015). That study concluded that air temperature is more clearly reflected than precipitation in a snowmelt-dominated catchment, represented by trends in flood magnitude and timing of snowmelt and spring flood. Numerous studies computed in North America and northern Europe linked changes in the timing of snowmelt onset to the increase in winter precipitation and air temperature leading to enhanced snowmelt during winter, which further causes the decreasing trend in the flood magnitude in a snowmelt-dominated catchment (e.g. Burn et al., 2010; Cunderlik & Ouarda, 2009; Birsan et al., 2005; Stewart et al., 2005).

The results for the annual minimum and maximum flows showed different changes (Figure 7). Trends for minimum flows (in Sjöberg et al., 2013) were mostly pointing towards an increase in minimum flow and more catchments showed significant trends. In contrast, the maximum flow showed both increasing and decreasing trends at non-significant levels and only one catchment
Bettina Matti

(Stenudden \( p = 0.02 \)) showed a significant (decreasing) trend. The results with increasing minimum and decreasing maximum flows further are indications for a dampening of the hydrograph and a shift from a snowmelt-dominated to a rainfall-dominated flow regime (Arheimer & Lindström, 2015; Dahlke et al., 2012). The maximum flow is likely to be more sensitive to changes in climate variables than the minimum flow. Linear rates of change for the maximum flow showed a larger range, although computed over one decade, whereas the linear rate of change computed by Sjöberg et al. (2013) showed less changes, even though calculated applying the entire period of record. In the Swedish Subarctic, the maximum flow therefore is likely to be more impacted by the change in climate than the minimum flow, which might be due to the more severe changes caused by a shift in the flow regime. In snowmelt-dominated catchments, the minimum flow is mostly occurring during winter and driven by precipitation in winter. In contrast, the maximum flow is driven by the snowpack accumulated during winter leading to the spring flood when snowmelt occurs or by heavy rainfall events during summer and autumn (Arheimer & Lindström, 2015; Hall et al., 2014; Sjöberg et al., 2013; Burn et al., 2010; Cunderlik & Ouarda, 2009). The trends in both annual minimum and maximum streamflow indicate permafrost thawing and an increase in active layer (Sjöberg et al., 2013; Callaghan et al., 2013). Increased groundwater flow and more capacity for water uptake were shown both in the trends for the minimum (increasing) and maximum (decreasing) flows (Dahlke et al., 2012).

The results of this thesis could possibly be linked to multi-decadal large scale atmospheric circulations as the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) or the East Atlantic (EA) pattern. As shown by Hannaford et al. (2013), these multi-decadal circulations over the Atlantic are affecting streamflow in northern Europe causing variability, which has to be taken into account interpreting the results of trend analyses. Dahlke et al. (2012) further showed that strong correlation between the mean summer flow and the East Atlantic pattern (EA) in the previous winter, as well as the NAO exists. The EA causes enhanced winter precipitation, whereas the NAO causes both above-average air temperatures and winter precipitation, but below-average summer precipitation. For catchments with permafrost in northern Europe, both mean summer flows and flood magnitude seem to be influenced by the EA and the NAO causing an increase in winter precipitation and snowpack leading to enhanced streamflow in spring and summer and a higher peak for the snowmelt flood (Hannaford et al., 2013; Dahlke et al., 2012). The influence of the EA and the NAO on streamflow due to enhanced winter precipitation is a possible explanation for decreasing trends in mean summer flow (Dahlke et al., 2012). The results of this thesis further agree with the AMO indices presented by Sutton & Hodson (2005), who showed the multidecadal fluctuations of the AMO causing above-average air temperatures, especially during summer, as well as enhanced precipitation in northern Europe. The flood in 2012 happening in the Övre Abiskojåkk catchment was possibly caused by a positive phase of the NAO, leading to enhanced winter precipitation, a bigger snowpack and therefore a higher peak in the snowmelt flood (NOAA, 2015). To be able to link the results reliable to these circulations, further analyses would have to be done.

The results of this thesis reflect the complexity of the hydrological system and interactions with climate variables and permafrost. Trends depend on the period of record, but also on multiple drivers causing the changes in the hydrology. These changes can further be caused by several variables at the same time, respectively the drivers influence each other causing variation in climate, leading to variability in streamflow. Woo & Thorne (2008) concluded that changes in the flood magnitude are likely to be driven by winter precipitation whereas air temperatures during winter influence the flood occurrence. For the Swedish Subarctic, Arheimer & Lindström (2015) concluded that due to the snowmelt-dominated regime, air temperature has a greater
impact on streamflow than precipitation. The absence of an overall pattern in trends of the analyses on the flood magnitude and flood occurrence is consistent with other studies on streamflow in northern Sweden, which found no consistent trends, whereas increasing trends in minimum flows and changes towards earlier snowmelt were detected (Arheimer & Lindström, 2015; Hall et al., 2014; Hannaford et al., 2013; Wilson et al., 2010).

4.2 Changes in extreme events

There is growing concern about an increase in extreme events, namely floods and droughts, globally. Numerous studies have shown increasing trends for extreme events (e.g. Hall et al., 2014; Kundzewicz et al., 2014). Callaghan et al. (2010) showed that extreme temperature and precipitation events have increased in northern Sweden, especially considering winter air temperatures, causing enhanced snowmelt during winter. Considering hydrological extreme events such as floods or droughts, the study by Lindström & Bergström (2004) detected an increase in floods in Sweden. Despite that, the study by Wilson et al. (2010) concluded that no indications towards an increase in extreme events were found for streamflow in northern Europe, which agrees with the study by Arheimer & Lindström (2015), which found no clear overall patterns for floods in Sweden over the last century with trends mostly at non-significant levels. Indications for a decreasing trend considering the 10-yr flood were detected. Nevertheless, they mentioned the decreasing trends for the snowmelt flood and increasing trends for the rainfall flood supporting a shift in flow regime.

The study by Dahlke et al. (2012) found contrasting trends in the flood percentiles for a catchment with substantial glacier coverage, which showed a significant increase in all flood percentiles considered (2, 10, 20, 50 and 100-yr floods), compared with a non-glacierized catchment, which showed a decrease in all flood percentiles at a 5% significance level. This study linked trends in the flood percentiles to the catchment properties such as glacier coverage and permafrost. Whereas glaciers led to an increase in maximum annual flow and an increasing trend in the flood percentiles due to the enhanced melting of glaciers in recent years, the decreasing trend in the non-glacierized catchment was detected due to the loss of permafrost, which allows the subsurface to buffer high flows and dampen the hydrograph. An increase in extreme events was further detected for the glacierized catchment. Comparing the non-glacierized Abisko catchment from Dahlke et al. (2012) with the Övre Abiskojäkk catchment in this thesis, which corresponds to the same catchment, contrasting results were found (Table 3 and Figure 9a,b). On the one hand this is based on the length of the record period considered and on the other hand on the timing of the most extreme floods in this catchment. The significant decrease found by Dahlke et al. (2012) was due to the long period of record (1919-2009) showing the flood in 1939 with a return period of more than 200 years. This time series ended in 2009, whereas this particular catchment did not experience the flood in 1995 or other floods in the 1990/2000s. The picture changes if the record period ends in 2013 due to the flood in 2012, which had a return period of more than 100 years considering the period 1986-2013 (Figure 8a). Both the trends would look differently if one would apply the entire period of record from 1919-2013. This example clearly shows the difficulties arising to interpret the results of both trend analyses and flood frequency analyses. Both analyses are highly dependent on long record periods and sensitive to the values in the beginning and in the end (Hannaford et al., 2013; Jones, 2011). Interpretations of linkages with climate variables and permafrost therefore have to be drawn with care, as mentioned by Hannaford et al. (2013).
The probability plots (Figure 8 and Appendix B) showed the tendency towards an increase in extreme events with the most extreme events over the entire period occurring more frequently in the wet period starting in the 1990s (Lindström & Bergström, 2004). Nevertheless, the trend analysis (Table 3 and Figure 9) showed that the selected flood percentiles were not necessarily showing significant increasing trends. All four catchments showing increasing trends in their flood percentiles experienced one to four of their largest floods in the last 20 years causing the positive slope of the trend. It is interesting, that catchments with short, medium-length and long record periods showed significant increasing trends in their flood percentiles. Positive changes for time series starting in the 1950s or later could be expected due to the dry period from the 1940s to 1990s (Lindström & Bergström, 2004). It is notable that the Solberg catchment showed a significant increase in the flood percentiles (for the 10 and the 20-yr floods), although this catchment contained a long period of record starting in 1911. The trend is due to the absence of a large flood in the 1920s, whereas the flood in the year 1995 showed a return period of 180 years (calculated over the period 1919-2013).

The flood in 1995 was remarkable since many catchments in Sweden experienced it as a large flood, which was possibly caused by enhanced precipitation during winter (Holmlund et al., 2005; Lindström & Bergström, 2004). This is the reason for the results showing significant decreasing trends over the common period, even for the Kaalasjärvi catchment, which showed a significant increase in the flood percentiles over the entire period. The catchments showing a decreasing trend over the common period were generally experiencing the flood in 1995, either as flood with a much higher return period or as the only flood in recent years. Catchments showing an increasing trend over both the entire and the common period of record are characterized by at least one extreme flood in the years 2010-2013 causing the positive slope. For these catchments, there are indications for an increase in extreme events. The results of this thesis generally agree with the outcomes of Arheimer & Lindström (2015). No overall patterns were detected analyzing the trends in the flood percentiles. There were both increasing and decreasing trends at significant and non-significant levels. Nevertheless, this thesis showed that there are indications for an increase in extreme floods in the Swedish Subarctic looking at the entire period of record available for each catchment. Clearly, there are processes occurring locally causing extreme flood events (Burn et al., 2010). This result agrees with the results from the trend analyses on the hydrological parameters which showed that processes are going on locally and a catchment’s reaction on a changing climate is depending on its properties such as state of permafrost, location (especially in terms of the Scandinavian mountain range) and size. Further, the extension of the area covered by lakes could possibly have an influence, especially on floods buffering high peak events and enhancing minimum flows during winter due to the loss of lake ice (Lindström & Bergström, 2004). This would further lead to a decrease in flood magnitude and a shift in flow regime in snowmelt-dominated catchments, as reported by Arheimer & Lindström (2015).

Analyzing the spatial distribution of the catchments showing significant changes in extreme events over the entire period of record (Gauträsk, Kaalasjärvi, Övre Abiskojåkk, Tängvattnet and Solberg), it is notable that all these catchments are located along the Norwegian border in the Scandinavian mountain range (Figure 1). Further, all these catchments show an above-average mean elevation and their area is smaller than 1500 km$^2$ (Table 1). The location close to the Scandinavian mountain range and the state of permafrost could influence the hydrology and its changes. This finding agrees with the study by Birsan et al. (2005), which positively correlated streamflow to the catchment’s elevation in Switzerland, meaning that catchments with higher
Trends in high peak flow generation across the Swedish Subarctic

elevation were likely to show increasing trends in streamflow. Winter precipitation falling as snow is especially important in these catchments, causing the snowmelt flood in spring. This further strengthens the theory, that atmospheric circulations are likely to influence changes in extreme events causing variability in precipitation and temperature, especially during winter (Birsan et al., 2005). The state of permafrost on the other hand seems not to influence the generation of high peak flows as much, since the catchments are located in the continuous, discontinuous and isolated permafrost zone (Table 1 in Sjöberg et al., 2013).

4.3 Uncertainties and difficulties

As mentioned earlier, there are uncertainties associated with computing trend analyses, as well as difficulties, especially in interpreting the results. Trend analyses are highly dependent on the period of record available and chosen. Interpreting trend analyses, the length of the record period should always be mentioned and kept in mind while comparing results. As showed in this thesis, trend analyses are especially sensitive to the values in the beginning and the end of the time series influencing the slope of the trend (Jones, 2011). Drawing conclusions based on time series, especially when relating the results to climate as in this thesis, always have to be done critically and the variability of climate and hydrology have to be kept in mind. As shown by Hannaford et al. (2013), the decadal-scale variability of atmospheric circulations causes fluctuations in the streamflow records. Long periods of record are therefore desired to be able to account for such long term variability. Since trend analyses on the past are often used to calibrate models predicting the future, it is especially important to be as accurate as possible about the past, where long term records are essential to be able to get the right trends. Hannaford et al. (2013) suggested a multi-temporal approach to account for uncertainties in trend analyses applying them on different periods of record. The approach with the trend analysis applied on the entire period of record and a common period is powerful and the results of all catchments over the common period can easily be compared. Nevertheless, 24 years of data is not representing a long term trend in hydrological systems, which show multidecadal fluctuations linked to climate, especially to long term atmospheric circulations (Khaliq et al., 2009).

The complexity of the hydrological system and interactions and feedbacks with climate variables and the cryosphere raise difficulties interpreting the results. Catchments are likely to react to changes locally, leading to different trends. Besides the cryosphere and climate variables, which are more regionally distributed, local parameters such as location, size and coverage with glaciers and lakes might further influence the hydrology and its changes. Developing new knowledge on hydrological systems is therefore desirable at catchment scales and with regional analyses in order to find consistency and overall patterns. Changes in hydrological systems have to be looked at generally, taking into account all aspects and variables influencing the hydrology. Detecting changes in the system is therefore a challenging and demanding purpose.

The choice of catchments for analyses of trends in the high peak flow was probably not optimal for the purpose of this thesis. Uncertainty arises due to the catchments located downstream of others (nested systems) creating sub-catchments and tributaries to downstream catchments. Extreme events might be affected downstream, either amplified or buffered, as shown by Pattison et al. (2014). On the other hand, analyzing downstream catchments can provide knowledge on the development and impacts of extreme events for downstream areas, especially in terms of human infrastructure. Nevertheless, this was not further considered for this thesis. The location of the gauging station measuring streamflow might affect the results of a trend analysis leading to a dampened signal for the flood generating process. This influences the interpretation of the
trend analysis and makes it difficult to distinguish between the climate variables forcing streamflow to change. The results of this thesis and the fact that no overall patterns in trends were detected might be caused by the location of the gauging stations. Besides, some of the gauging stations considered in this thesis are located at the outflow of a lake, which could enhance the problem of buffering and mixing the signals of the flood generating processes, as shown by Woo & Thorne (2008). This is possibly the explanation for the presence of multiple day flood peaks, as detected in this thesis. Analyzing the flood magnitude of the Abisko catchment for example, the value for the annual maximum flow was detected on three days in a five day period. This might arise due to the location of the gauging station at the outflow of Lake Torneträsk, a big lake covering approximately 14% of the catchment’s area, and would support the hypothesis that lakes might act as buffers on floods showing changes in their hydrology such as less ice cover and earlier ice break up (Callaghan et al., 2013; Lindström & Bergström, 2004). The issue of multiple days showing the annual maximum flow was not further considered for the analysis. Rather, the first appearance of the annual maximum flow was used for the analysis, assuming that the uncertainty arising were negligible, since this phenomenon is not caused by upstream flow regulation.

Further, there were some methodological uncertainties, which have to be kept in mind. All analyses on trends are based on statistical models. These approaches are powerful since they are well studied, designed for special purposes (e.g. extreme values) and able to quantify a problem. Nevertheless, they are models and an idealization of nature, which is always linked to uncertainties. The return periods for large floods are especially uncertain as shown in the probability plots of the catchments considered in this thesis (Figure 8 and Appendix B). The largest floods are generally deviating more from the idealized Gumbel distribution than floods with a return period of 1 to 10 years. This is further indicated by the widening of the Kolmogorov-Smirnov bounds for high and low values, allowing more values to fall between the bounds showing the confidence interval. To analyze the stationarity of flood percentiles, a moving window approach was applied, which is a powerful tool. Nevertheless, there are uncertainties, since the Gumbel distribution was fit to only ten years of data, which causes the goodness-of-fit more likely to show low confidence. This was expressed by the probability plot correlation coefficient (PPCC) test, which resulted in lower values than the critical values (Table 2 in Appendix A). Further, five year windows were applied in the beginning and the end of the record period to be able to plot more years, which resulted in even lower r-values. Since only one or two windows showed an r-value below the assumed critical value of $r = 0.80$ and the mean r-value of the particular catchments was accepted by the critical values for the PPCC test, the results were accepted, even if not all windows showed an r-value above 0.80.

## 4.4 Prospects

The results of this thesis showed that there is uncertainty in the interpretation of changes happening with floods in northern Sweden. To be able to improve the analyses and to be able to cover more parameters influencing changes in the hydrological system, more analyses should be done and the approaches should be adapted. Due to time limits, the following suggestions could not be covered by this thesis.

The analysis of the flood magnitude as a seasonal analysis for the mean flow would be desirable as done by Wilson et al. (2010). The shift in flow regime suggested by Arheimer & Lindström (2015) could be proved by separating the spring and the autumn flood analyzing changes for both the floods separately. The importance of distinguishing between annual and seasonal trends was
pointed out by Stahl et al. (2010). To be able to determine the drivers of changes in the hydrological system, further analyses on climate variables such as air temperature, precipitation as well as permafrost would be desired at catchment scales. Cross-correlations should be applied between changes in the hydrology and the climate variables and atmospheric circulations, as done by Dahlke et al. (2012). The results in this thesis suggested that lakes possibly influence the generation of high peak flows, due to changes in the hydrological system of the lake itself. Callaghan et al. (2013) showed that ice break up of Lake Torneträsk is happening earlier and the extension of lake ice has decreased, leading to changes in the spring flood caused by the melting of snow and ice in spring. It is suggested that, if catchments with substantial lake coverage are analyzed, changes in the hydrology of the lake and its ice cover should be taken into account.

Hannaford et al. (2013) suggested improvements for trend analyses on hydrological purposes using a multi-temporal approach to be able to get an appropriate trend accounting for multi-decadal variability in climate caused by large scale atmospheric circulations. It is further desired to apply a trend analysis on a period of record as long as possible to be able to account for long term variability in the results of the trend analysis. Hall et al. (2014) further suggested that a combined approach of data-based trend analyses covering the past and models predicting the future is desired to be able to give recommendations for water management strategies.
5 Conclusions

This thesis showed that there are changes occurring in the hydrological system of the Swedish Subarctic. Nevertheless, only a few catchments showed significant trends in the hydrological parameters analyzed. No overall patterns could be detected for the Swedish Subarctic, which points out the importance of trend studies at catchment scales, since changes in the hydrology are likely to happen locally. This is especially important due to the complexity of the hydrology in cold climates, where the hydrology is strongly linked to climate and the cryosphere. Indications towards earlier snowmelt onset and less mean summer flow were detected for the catchments considered. Further, trends indicating a lower flood magnitude and an earlier timing of the snowmelt driven spring flood were found. Combining the results of the trend analysis on the different hydrological parameters, indications towards a shift in flow regime from snowmelt to rainfall-dominated were found, which is characterized by earlier snowmelt onset and flood occurrence, as well as a decrease in flood magnitude. Indications for a development of an intermediate, bi-modal flow regime as suggested by Cunderlik & Ouarda (2009) were found. Analyzing selected flood percentiles for stationarity, no clear patterns were detected. Indications towards an increase in extreme events were found over the entire period, especially for catchments located close to the Swedish mountain range, whereas the flood in 1995 influenced the results of this analysis over the common period.

The comparison between annual minimum and maximum flows showed substantial differences in trends. Increasing trends were detected for annual minimum flows, whereas annual maximum flows showed more variability and indications towards lower flows. These contrasting trends are likely to be caused by the degradation of permafrost and the increase in active layer, creating new subsurface flow paths and an enhanced groundwater flow, but also acting as a buffer for high peak flows (Sjöberg et al., 2013; Dahlke et al., 2012).

The drivers of changes in hydrological systems in the Swedish Subarctic are difficult to determine due to interactions and the complexity of cold climate systems. The hydrology is determined by changes in air temperature and precipitation at multidecadal, annual and seasonal time scales, caused by large scale atmospheric circulations over the North Atlantic. It is hard to distinguish between the climatic variables influencing hydrological systems. The results of this thesis suggest that changes in air temperature are more clearly reflected in the streamflow than precipitation due to the snowmelt-dominated flow regime (Arheimer & Lindström, 2015; Wilson et al., 2010).

The uncertainties and variations in time applying trend analyses mentioned by Hannaford et al. (2013) were clearly showed in this thesis. By comparing the results over the entire period with the results over the common period (1990-2013), the importance of a long record period was shown, which is needed to be able to take into account the multidecadal variability of the atmospheric circulations over the North Atlantic. It further showed the sensitivity of trend analyses on the conditions in the beginning and in the end of the record period (Jones, 2011).

In general, the results of this thesis agree with previous studies on changes in hydrological systems of northern Sweden showing that there are indications, but no clear patterns towards a shift in flow regime and a decrease in annual maximum flows (Arheimer & Lindström, 2015; Hall et al., 2014; Hannaford et al., 2013; Wilson et al., 2010). Further research on changes in hydrological systems should focus on seasonal and multi-temporal trend analyses of streamflow as well as correlation analyses with climatic parameters to be able to get accurate results of the trend analyses.
Acknowledgements

First of all, I would like to thank my supervisors Steve Lyon and Helen Dahlke for great support and guidance throughout this thesis. You always had an open ear for all my problems and worries and made sure that I kept track of my project and didn’t get lost in the complexity of the matter. A big thanks goes to Norris Lam, who helped during the programming part and taught me in trouble shooting. Thanks also to Ylva Sjöberg for providing the data. Last but not least, I would like to thank my family and friends for keeping up the motivation and helping through hard times.
References


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Appendix A – Tables

Table 1: Critical values for $\omega_1$ and $\omega_2$ applied for the Kolmogorov-Smirnov test for goodness-of-fit. Table 2 in Chowdhury et al. (1991).

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<th>$\tau_2 = 0.6$</th>
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The $\tau_2$ are regional values.

Table 2: Lower critical values of the PPCC test for the Gumbel distribution using Gringorten’s plotting position ($p_i = (i-0.44)/(n+0.12)$). Table 7.7 in Loucks et al. (2005).

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Appendix B – Results flood frequency analysis

Probability plots showing the quantiles of the fitted Gumbel distribution using Gringorten’s plotting position plotted against the observed values $X_{i,m} (m^3/s)$. The solid line represents the idealized Gumbel distribution, the dashed lines are the Kolmogorov-Smirnov bounds at a 95% confidence interval. Exceedance probabilities and return periods of a certain flood event are plotted on the secondary x and y-axis, respectively. Probability plots for all catchments are shown, in alphabetical order (except the Gauträsk and Övre Abiskojäkk catchments, which are shown in Figure 8 in the results part).
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