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HYDROLOGICAL DROUGHTS IN SWEDEN

Mapping of historical droughts and identification of primary driving climate variables and catchment properties

Hugo Rudebeck

ABSTRACT

HYDROLOGICAL DROUGHTS IN SWEDEN: MAPPING OF HISTORICAL DROUGHTS AND IDENTIFICATION OF PRIMARY DRIVING CLIMATE VARIABLES AND CATCHMENT PROPERTIES

Hugo Rudebeck

This study investigated the relationship between hydrological, and to some extent, meteorological droughts, and meteorological variables and catchment characteristics in 235 Swedish catchments between 1983 and 2013. This was done in order to investigate what factors affect the drought sensitivity in Swedish catchments and to map the occurrence of droughts in Sweden between 1983 and 2013. There have been studies about which meteorological phenomena and catchment characteristics that promote hydrological droughts, but for Sweden this is relatively unexplored. To investigate droughts during the study period three indices were used: the Standardized Precipitation Index (SPI), which is an index for meteorological droughts, the Standardized Streamflow Index (SSI), which predicts hydrological droughts and a threshold index for streamflow droughts. These indices were used to identify the number of drought events and the total number of drought days. For the majority of the 235 Swedish catchments there were no significant trends for the number of drought events or the total number of drought days during the 30-year period. The SPI and the SSI were found to correlate best in time when adding a one-month lag period to the SSI time series. The correlations between the indices and the meteorological variables and the catchments properties varied depending on how the catchments were grouped according to latitude or elevation. For example, the number of drought events was positively correlated to the mean elevation of the catchments in north and central Sweden when using the SSI while there were no significant correlations with elevation in southern Sweden. Another example is that it was almost only in northern Sweden where significant correlations between the percentage of bedrock and drought characteristics were identified. The percentage of bedrock can be used as an indication for how much groundwater a catchment can store. The correlations also look different for the different indices. For example, when looking at all catchments together the number of drought events identified with the SPI was negatively correlated to latitude and mean elevation while the number of drought events identified with the SSI was positively correlated to the same variables. For further research into this topic it would be wise to study winter and summer droughts separately to better identify which are the driving variables.

Keywords: hydrological droughts, drought propagation, drought indices, SSI, threshold index, SPI, catchment properties and drought events.

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REFERAT

HYDROLOGISKA TORRPERIODER I SVERIGE: KARTLÄGGNING AV HISTORISKA TORRPERIODER OCH PRIMÄRA KLIMATOLOGISKA DRIVVARIABLER OCH AVRINNINGSOMRÅDESEGENSKAPER

Hugo Rudebeck

I den här studien undersöktes sambanden mellan hydrologiska, och till viss del meteorologiska, torrperioder och bakomliggande meteorologiska drivvariabler och avrinningsområdesegenskaper i 235 svenska avrinningsområden mellan 1983 och 2013. Detta gjordes i syfte att undersöka vilka faktorer som påverkar känsligheten för torka i svenska avrinningsområden och för att kartlägga förekomsten av torrperioder i Sverige mellan 1983 och 2013. Internationellt finns det studier på vilka meteorologiska fenomen och egenskaper hos avrinningsområden som leder till risk för fler torrperioder, men för Sverige är det ett relativt outforskat område. För att undersöka torrperioder under den aktuella perioden användes tre index: Standardized Precipitation Index (SPI), vilket är ett index för meteorologiska torrperioder, Standardized Streamflow Index (SSI), som används för hydrologiska torrperioder och ett tröskelvärdes-index för att identifiera hydrologisk torka. Indexen användes för att identifiera antalet torrperioder och totala antalet dagar med torka under studieperioden. För majoriteten av de 235 avrinningsområdena gick det inte att se några signifikanta trender för antalet torrperioder eller totala antalet dagar med torka under perioden 1983-2013. SPI och SSI korrelerade bäst med varandra över tiden när SSI-tidsserien försköts med en månad. Korrelationerna mellan torrperioderna identifierade med de olika indexen och de meteorologiska variablerna och avrinningsområdesegenskaperna varierade beroende på hur avrinningsområdena grupperades efter latitud eller medelhöjd. Till exempel, i norra och centrala Sverige korrelerade antalet torrperioder för SSI positivt med medelhöjden medan det i södra Sverige inte fanns några signifikanta korrelationer. Ett annat exempel är att det nästan bara var i norra Sverige som det fanns korrelationer mellan procenten berggrund och de identifierade torrperiodsegenskaperna. Procenten berggrund i jordlagret kan användas som en indikation på hur mycket grundvatten som kan lagars i ett avrinningsområde. Korrelationerna skiljde sig också åt för de olika indexen. Till exempel, sett över alla avrinningsområden så var antalet torrperioder beräknat med SPI negativt korrelerade med latitud och medelhöjd medan antalet torrperioder beräknat med SSI var positivt korrelerade med dessa egenskaper. För vidare forskning inom detta område rekommenderas att titta separat på vinter- och sommartorkor för att bättre kunna identifiera potentiella drivvariabler.

Nyckelord: hydrologisk torka, propagering av torrperioder, torkindex, SSI, tröskelvärdes index, SPI, avrinningsområdesegenskaper och torrperioder.

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PREFACE

This master thesis was done within the Master Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences. The project supervisor was Claudia Teutschbein at the Department of Earth Sciences, Uppsala University and the subject reviewer was Thomas Grabs at the Department of Earth Sciences, Uppsala University. I would like to thank them both for their support, guidance and advices throughout this process.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Vattenbrist eller torka är ett fenomen som många förknippar med nyhetsrapporteringar från andra delar av världen men det kan även drabba Europa och Sverige. Under 2016 och 2017 blev vattenbrist ett aktuellt ämne även i Sverige då det rapporterades om låga grundvattennivåer på flera håll i landet och lokalt infördes även restriktioner på vattenförbrukningen. Vetenskapligt sett beskrivs torka bäst som en avvikelse från normala förhållanden vad gäller nederbörd eller vattenföring. I den vetenskapliga litteraturen brukar torrperioder delas in i meteorologiska, markvatten, hydrologiska eller socioekonomiska torrperioder. Meteorologiska torrperioder sker då nederbörden är lägre än det normala under en period. Markvatten- eller jordbrukstorka är då det blir brist på vatten i marken vilket kan leda till vattenstress för växter och förlorade skördar. Hydrologiska torrperioder infaller då grundvattennivåerna eller vattenföringen i vattendragen är under det normala. Socioekonomiska torrperioder är då de tidigare nämnda fenomenen får en påverkan på samhället. En torrperiod börjar vanligtvis med en meteorologisk torka orsakad av låga nederbördsmängder som därefter kan utvecklas till en markvattentorka och/eller en hydrologisk torka, dessa kan slutligen resultera i en socio-ekonomisk torka. För att kunna följa utvecklingen av torrperioder och kunna utfärda varningar i tid har man tagit fram flera index för att definiera torrperioder. Internationellt sett finns det flera studier på vilka orsaker som ligger bakom torrperioder och hur egenskaper i avrinningsområden påverkar utvecklingen av torrperioder men när det gäller torrperioder i Sverige finns det stora kunskapsluckor.

Den här studien har undersökt vilka egenskaper i svenska avrinningsområden som leder till ökad känslighet för torrperioder. Studien har undersökt torrperioder mellan 1983 och 2013 i 235 svenska avrinningsområden med hjälp av tre olika index: *Standard Precipitation Index* (SPI), *Standard Streamflow Index* (SSI) och ett tröskelvärdesindex *threshold index* på engelska. Både SPI och SSI använder ackumulerad data för olika tidsperioder. Indexen användes för att undersöka huruvida det inträffat några torrperioder under den aktuella tidsperioden samt vilka karaktärer hos avrinningsområdena som kan kopplas till förekomsten av torrperioder. Studien undersökte också hur väl resultaten mellan de olika indexen och mellan de olika ackumuleringsperioderna överensstämde med varandra. Utöver det undersöktes även om meteorologiska och hydrologiska torrperioder blivit vanligare under tidsperioden 1983-2013. Slutligen undersöktes också hur väl SPI och SSI korrelerar med varandra för olika tidsförskjutningar för att undersöka vilken tid det tar för en meteorologisk torka att resultera i en hydrologisk torka.

Det var möjligt att identifiera flera torrperioder under perioden 1983-2013 med både SPI och SSI, indexen uppvisade liknande mönster över tid och det gick att urskilja skillnader mellan norra, södra och centrala Sverige. Två stora landsomfattande torrperioder 1995-1996 och 2002-2003 gick att urskilja och både 1996 och 2002 beskrivs som torra år i gamla rapporteringar. SPI och SSI korrelerade bättre ju längre ackumuleringsperioderna var och en månad var den tidsförskjutning som gav bäst korrelation för alla ackumuleringsperioder. Utifrån detta resultat är det möjligt att dra slutsatsen att den generella tiden det tar för en meteorologisk torka att övergå i en hydrologisk torka i Svenska avrinningsområden är cirka en månad eller mindre. Gällande vilka avrinningsområdesegenskaper som mest påverkar förekomsten av torrperioder skiljde sig resultaten åt mellan olika delar av landet. Sett över hela landet finns det indikationer på att de hydrologiska torrperioderna blir fler men kortare ju längre norrut man kommer i landet, detsamma gäller även ju högre upp avrinningsområdena är belägna. Bortser man däremot från de avrinningsområden som ligger i fjällen så minskar både antalet hydrologiska torrperioder och totala antalet dagar med torka ju längre norrut i landet man kommer. Delar man upp Sverige i tre olika delar i norra, centrala och södra Sverige kan man se olika mönster för vilka karaktärer som korrelerar med torrperioder. I norra Sverige så ökar antalet torrperioder ju mer berggrund som finns i jordlagret samt ju högre upp avrinningsområdena är belägna. Högre andel berggrund i jordlagret innebär teoretiskt sett mindre grundvatten vilket kan antas öka känsligheten för att torrperioder ska inträffa, så detta resultat är inte helt oväntat även om det inte syns i de andra delarna av Sverige. I centrala Sverige minskar antalet hydrologiska torrperioder med storleken på avrinningsområdena samt med hur mycket jordbruk, skog, sjöar och vattendrag de innehåller. Antalet hydrologiska torrperioder minskar också om vattendragen i avrinningsområdena är mer reglerade i centrala Sverige vilket kan förklaras med att regleringen leder till mer konstanta vattennivåer. I södra Sverige finns det också ett negativt samband mellan antalet hydrologiska torrperioder och hur mycket sjöar och vattendrag som finns i avrinningsområde samt hur reglerade de är. I majoriteten av de 235 avrinningsområdena har det inte skett någon ökning eller minskning av antalet torrperioder under den tidsperiod som studien behandlat. Men negativa trender för antalet torrperioder och antalet dagar med torka observerades för alla index under studieperioden i ett område i de centrala delarna av södra Sverige. Dessutom observerades positiva trender för antalet torrperioder och antalet dagar med torka för de hydrologiska indexen, *SSI* och tröskelvärdesindexet, i delar av Skåne, Jämtland och Ångermanland. I jämförelsen hur de olika indexen och ackumuleringsperioderna överensstämde i skattningarna av antalet torrperioder så visa sig resultaten erhållna med SPI vara mer känsligt för vilken ackumuleringsperiod som valdes än för SSI. För skatta totala antalet dagar med torka var SSI känsligare för vilken ackumuleringsperiod som valdes än SPI. För att fördjupa studien och förbättra resultaten skulle en möjlighet vara att analysera sommar- och vintertorkor separat.

CONTENTS

1. INTRODUCTION

Droughts are natural hazards caused by a lack of precipitation that can occur in any region of the world (World Meteorological Organization, 2017). Compared to other natural hazards like floods and earthquakes, drought events develop slower and are sometimes called ‘creeping disasters’ (Van Loon, 2015). Droughts can have big impacts on societies causing both economic as well as human losses especially in regions with political or civil unrest, which are extra vulnerable. Three big drought disasters in East Africa in 1975, 1983 and 1984 caused more than 600 000 deaths (World Meteorological Organization, 2014). However, the occurrence of droughts is not a phenomenon only restricted to other parts of the world. Europe has been hit by several droughts in the last century. For example, on average 15 % of the EU population was affected by droughts each year during the period of 2006-2010 (European Environmental Agency, 2016). In 2016 the Geological Survey of Sweden (SGU, from its Swedish name) reported the driest year in 40 years and during 2017 the situation with low groundwater levels and streamflows in many part of the country continued. Already during the spring of 2017, the situation was so severe in some areas of Sweden that local restrictions had to be issued to save water (Geological Survey of Sweden, 2017).

Droughts can be divided into four subdivisions: meteorological droughts based on a lack in precipitation, agricultural droughts based on insufficient soil moisture, hydrological droughts based on groundwater and streamflow shortages and when these droughts affect the society they develop into socio-economic droughts (Van Loon and Laaha, 2015). This study will focus on hydrological droughts which are defined as water levels below normal in reservoirs, streams, lakes and groundwater storages (Van Loon, 2015; Van Laanen, et al., 2012). The impacts from hydrological droughts affect sectors like water supply, crop irrigation, electricity production, transport and navigation among others (Van Loon, 2015). Hydrological droughts are caused by the propagation of meteorological droughts, but not all meteorological droughts develop into a hydrological drought (Van Laanen, 2006).

There is a growing awareness that droughts are not just characterized by precipitation deficiency, but that drought development is a complex process which is also affected by hydrological processes (Van Loon, 2015). However, it is still not completely clear how climate and catchment characteristics relate to hydrological droughts. There have been studies on the area e.g. by Van Loon and Laaha (2015) where they looked at catchments in Austria. But the impacts of climate and catchment characteristics found there are not necessarily the same that will be promoting droughts in Sweden due to different conditions. Droughts develop differently in seasonal climates than in relatively constant climates. In constant climates, the main factor promoting droughts is a below normal precipitation, sometimes in combination with increased evapotranspiration (Van Loon, 2015). In warm seasonal climates droughts in the rain season, where most of the recharge of water bodies happens, can result in droughts in the dry season. Snow accumulation and frozen soils are factors that prevent recharge and together with the timing of the snow melt these factors impact the drought development in climates with periods with below zero temperatures (Van Loon, 2015).

1.1. BACKGROUND

1.1.1. Drought definition

Due to the complexity of the drought phenomenon there is no universal way to define a drought but it should not be confused with aridity, desertification, low flow or water scarcity. Aridity describes an arid and dry climate which is a permanent condition compared to droughts which are temporary phenomena (Van Loon, 2015). Desertification is related to droughts but is the result of inappropriate land use and other human activities causing land degradation. Desertification can however be further aggravated by droughts (European Commission, 2016 a). Low flows are low streamflows, which do not necessarily coincide with a drought, like 'normal' annual low flows. Water scarcity is a phenomenon that is caused partly or fully by human impacts (Seneviratne et al., 2012) where the water resources are insufficient to cover requirements in the long term. Though separate phenomena, water scarcity and droughts might promote and aggravate the effects of each other (European Commission, 2016 b).

The simplest way to define a drought is a water deficit relative to normal conditions (Sheffield and Wood, 2011). What are considered normal conditions depends on the activities the water is used for. For example, seasonal flow deviations can have serious impacts on hydroelectrical production whereas a specific minimum water level is required for navigation or ecosystems (Van Loon, 2013). This is governed by the hydrological cycle which describes the movement of water through the atmosphere, land and oceans. In scientific literature droughts are generally divided into four different classifications based on the propagation of water through the hydrological cycle (e.g. Sheffield and Wood, 2011; Van Loon, 2013; Van Loon, 2015; Mishra and Singh, 2010):

- meteorological drought is defined as a deficiency in precipitation for a period of time over an area.

- soil moisture drought or agricultural drought refers to a deficiency in soil moisture. Soil moisture droughts reduce the available water for plants and are therefore strongly linked to crop failure, thus they are also referred to as agricultural droughts.

- hydrological drought refers to a period with deficiencies in surface and subsurface water systems. Examples of hydrological droughts include below-normal water levels in lakes and reservoirs, below-normal groundwater levels and decreased river discharge.

- socio-economic drought is associated with a combination of the three above mentioned drought types. It refers to a failure of water systems to meet water demands which might lead to social and economic impacts.

1.1.2. Drought propagation

In this study drought propagation refers to the development of one type of drought into another and not to the spatial development of a drought.

A hydrological drought usually starts with a meteorological drought. The drought development generally starts with a prolonged lack of precipitation as an effect of atmospheric processes. Changes in temperature are another trigger that may start a hydrological drought either by evapotranspiration or by snow accumulation. Both temperature and precipitation anomalies can be related to large scale atmospheric processes. In some parts of the world temperature and precipitation anomalies can be related to the North Atlantic Oscillation (NAO) and in other parts El Niño-Southern Oscillation (ENSO) is the influencing process (Van Loon, 2015). During dry spells, precipitation deficiency often occurs simultaneously with increased evapotranspiration which lead to depletion of soil moisture and less surface runoff and interflow. Surface runoff and interflow are the fast mechanisms contributing to the streamflow, but these are often limited during a dry spell. Depletion of soil moisture leads to soil moisture droughts which in turn can lead to water stress for plants and crop failure. It also results in less groundwater recharge and declining groundwater levels and drying aquifers. Discharge from the groundwater is a slow mechanism contributing to the streamflow and during dry spells it might be the main contribution the streamflow (Van Loon, 2015). All the processes above might cause the depletion of water systems which then cannot meet the demands of society and thus develop into a socio-economic drought.

Drought propagation is controlled by processes affected by climate and catchment properties, these processes include: the combination of several meteorological droughts into one prolonged hydrological drought, the attenuation of meteorological droughts developing into soil-moisture or hydrological droughts because of the storage of water in catchments, the time it takes for a meteorological drought to develop into a soil-moisture or hydrological drought which is referred to as lag time (Van Loon, 2015).

1.1.3. Indices

Drought indices are required to identify drought characteristics such as timing, duration, severity and spatial extent (Van Loon 2015). Drought indices can help decision-makers in the drought prevention planning and to decide where to put resources during an ongoing drought event. There is a vast list on available drought indices but some of the commonly used indices are:

- **Aridity Index (AI)** – Used to determine drought development over shorter timescales based on monthly mean temperature and precipitation. The drought is determined by the ratio of precipitation to mean temperature. It can use different time steps but does not take into account that droughts can carry over from one year to the next (World Meteorological Organization, 2016).
- **Palmer Drought Severity Index (PDSI)** – The Palmer Drought Severity Index is based on temperature, precipitation and the water holding-capacity of soils. It takes into account the storage of water in the soils and losses through evaporation, however, it does not handle frozen soils very well (World Meteorological Organization, 2016).
- **Standard Precipitation Index (SPI)** – Based on historical precipitation data to estimate the probability of precipitation. The SPI is recommended by the World Meteorological Organization to be used as the main index in the monitoring of meteorological droughts. The index can be calculated on different timescales which broadens the applications of the index. It is based solely on precipitation data which makes it easy to use but that is also the weakness of the index, not accounting for the other factors like temperature that affects the water balance (World Meteorological Organization, 2016). Several other indices have been

based on the SPI using other input variables than precipitation such as runoff, groundwater levels or reservoir levels.

- **Standardized Precipitation Evapotranspiration Index (SPEI)** – Based on the SPI but through a basic water balance equation it also takes into account the temperature. The index identifies both wet and dry extremes. It is a monthly index and therefore droughts that develop swiftly might not be identified very fast (World Meteorological Organization, 2016).
- **Streamflow Drought Index or Standardized Streamflow Index (SSI) –** An index based on streamflow data computed in the same way as the SPI. The results are also similar to SPI identifying both wet and dry periods as well as the severity. The SSI can be used for various timescales (World Meteorological Organization, 2016).
- **Standardized Snow Melt and Rain Index (SMRI) –** Computed in a comparable way to the SPI but includes both precipitation and snow melt deficits (Van Loon 2015). The input parameters are streamflow, temperature and precipitation. It takes into account the snow accumulation through the temperature and precipitation data and considers contributions to streamflow from snow melt. The fact that snow depth or snow water equivalent are not accounted for could result in biased estimations of the runoff (World Meteorological Organization, 2016).
- **Surface Water Supply Index (SWSI)** – Based on the Palmer Drought Severity index (Doesken, McKee and Kleist, 1991) but the SWSI index includes all the water resources which give a good picture of the hydrological status. Inclusion of additional data requires the index to be recalculated which could make it problematic to obtain homogenous time series (World Meteorological Organization, 2016).

There are also approaches to monitor droughts based on predefined thresholds. These thresholds are based on percentiles, e.g. the 80th percentile of the flow duration curve for each time step, alternatively a fixed threshold can be used for the whole period. A drought event starts when the flow falls below the threshold and ends when the flow is above the threshold again (Van Loon and Laaha, 2015; Van Loon, 2015). An advantage of the threshold method is that it is possible to determine the deficit volume. On the other hand, there are no standard drought classes for the threshold index and it is impossible to completely avoid subjective choices when deciding which threshold to use (Van Loon, 2015).

1.2. OBJECTIVES

In order to better understand which meteorological variables and catchment specific parameters that affect the development of hydrological droughts in Sweden this study analyzed historical droughts in 235 catchments in Sweden. The objectives were:

- investigate hydrological droughts in Sweden during the period of 1983 to 2013 with the help of suitable drought indices.
- investigate correlations between the number of droughts and the number of drought days that have occurred during the study period with catchment specific parameters.

- investigate correlation and any eventual lag time between a precipitation-based index and a streamflow-based index in order to study the time it takes for a meteorological drought to develop into a hydrological drought in Swedish catchments.
- investigate how the indices correlate with each other in regards to predicting the number of droughts and how long they last.
- investigate if hydrological or meteorological droughts have become more frequent in the 235 catchments during the study period.

2. METHODS

2.1. STUDY AREA AND DATA

Geospatial data including streamflow and precipitation for 235 Swedish catchments (Fig. 1) was provided by the Swedish Meteorological and Hydrological Institute's (SMHI) Swedish water archive (SVAR) (Eklund, 2011), which is a database containing information about Swedish catchments, rivers, lakes and marine areas (Henestål et al., 2015).

The geospatial data was complemented with land cover data for the catchments obtained from the CORINE land cover project CLC2006 (European Environmental Agency, 2007). The data set contained the mean elevation, size and latitude for all catchments. It also included data about how regulated the catchments are, the percentage of bedrock in the soil cover plus the amount of wetlands, lakes and streams, forest and agriculture in the catchments. The range of catchments varied from the lowlands of southern Sweden to catchments located in the mountains bordering Norway in the north west with the highest mean elevation being just above 1000 m a.s.l. The size of the catchments ranges from 0.8 km^2 to almost 4700 km^2. The southernmost catchments are located at latitude 55.45 and the northernmost at latitude 68.37. See Figure 2 for a comple overview of the catchment property data. Maps showing the land use and evelation can be found in Figure 3 and Figure 4 respectively.

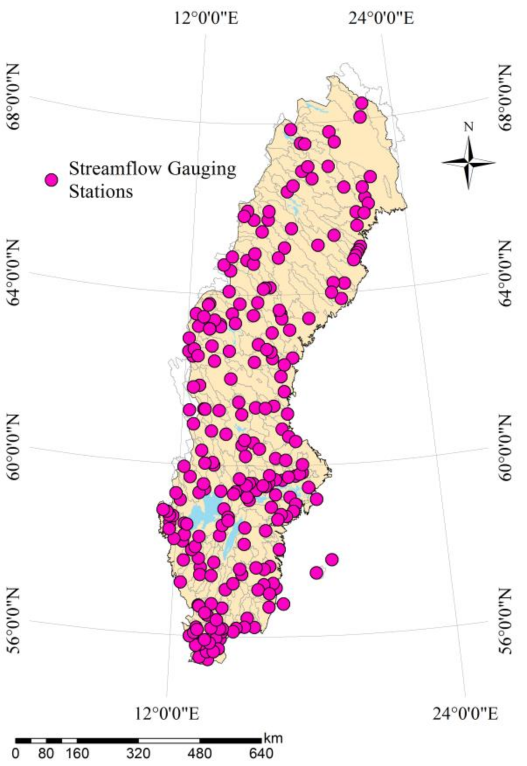

Figure 1 Locations of the 235 streamflow gauging stations for which streamflow and precipitation data were collected. Data obtained from the Swedish water archive SVAR (Eklund, 2011).

The streamflow and precipitation data used in this study were from the period October 1 1982 to September 30 2013. The precipitation and streamflow data series were chosen as to not contain any gaps of no data for more than nine consecutive days. Some data series contained single gaps of missing data that were shorter than four consecutive days which were filled using linear interpolation. Gaps of missing data that were between four or nine consecutive days long were filled using model data from SHMI (S-HYPE). In addition, the last day of all leap years was removed to have consistent annual series of 365 days.

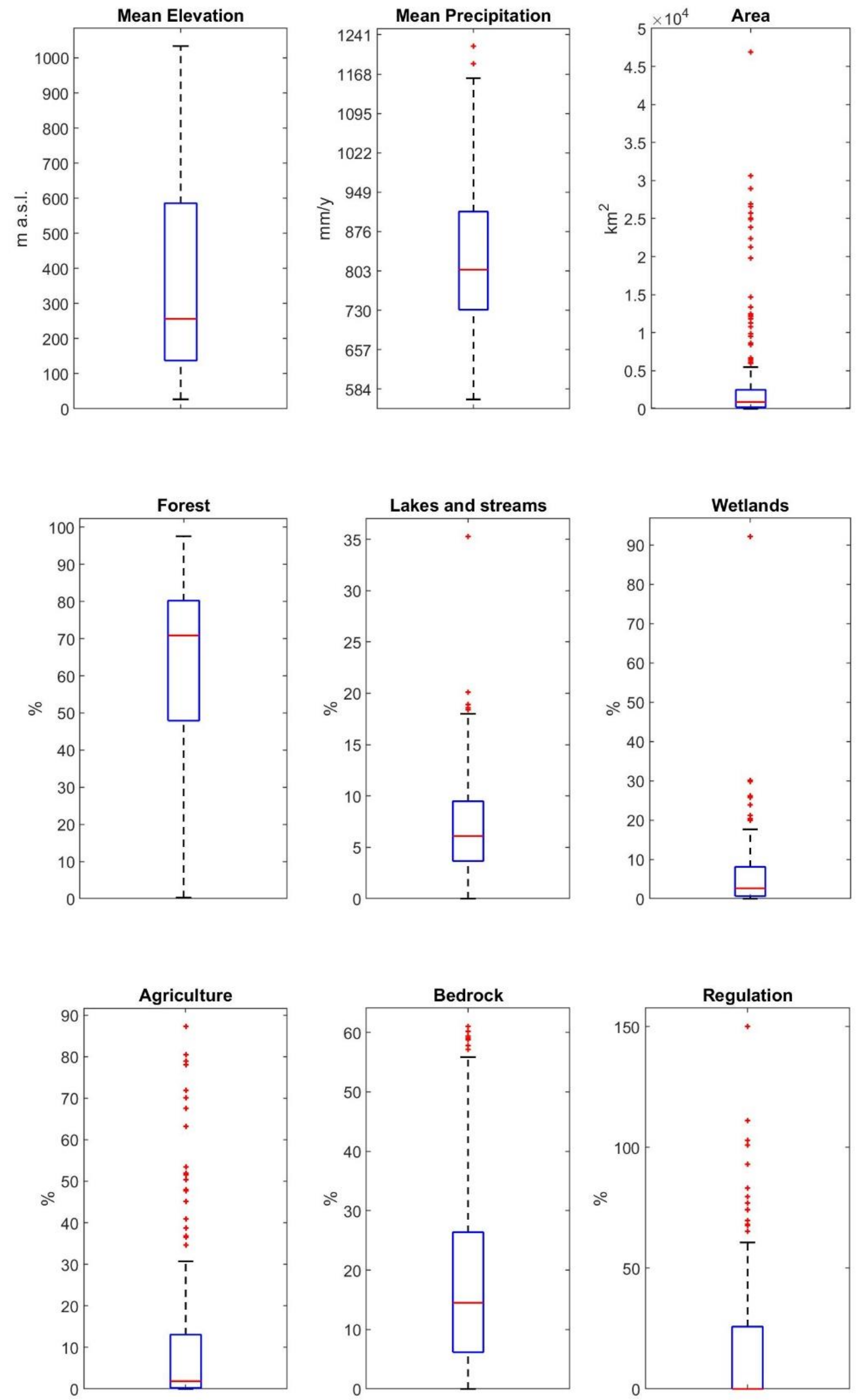

Figure 2 Box plots showing the range of the different catchment properties for the 235 catchments. The upper and lower limits of the boxes represent the 75th and the 25th percentiles respectively, the red line represents the sample median. The whiskers are located at 1.5 times the interquartile range from the 75th and the 25th percentiles, extreme values outside the whiskers are marked with red crosses. N.B. the ranges of the y-axes vary for the different box plots.

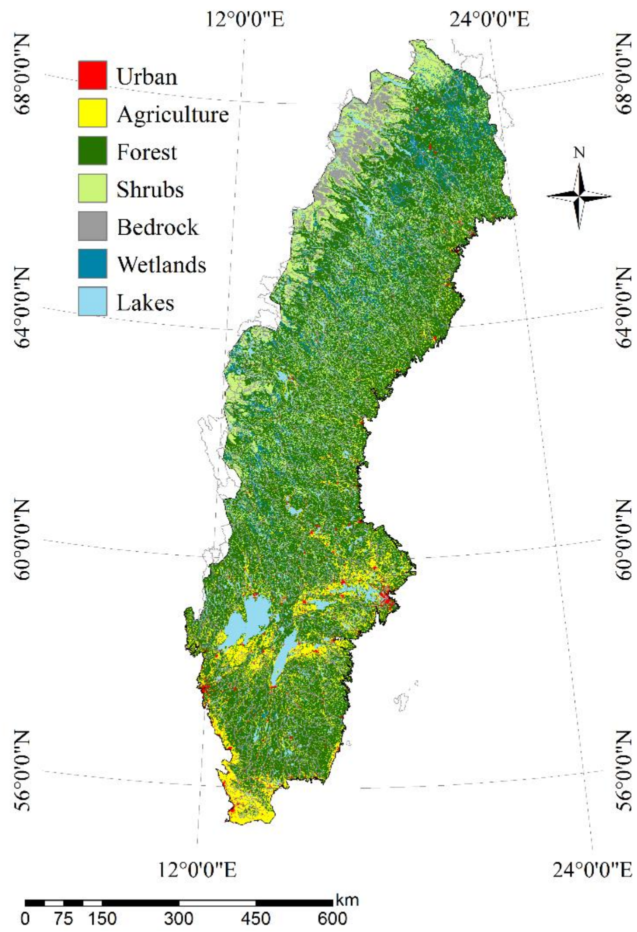

Figure 3 Land use in Sweden, showing the spatial extent of urban areas, agriculture, forest, shrubs, bedrock, wetlands and lakes. The land cover data for the catchments was obtained from the CORINE land cover project CLC2006 (European Environmental Agency, 2007)

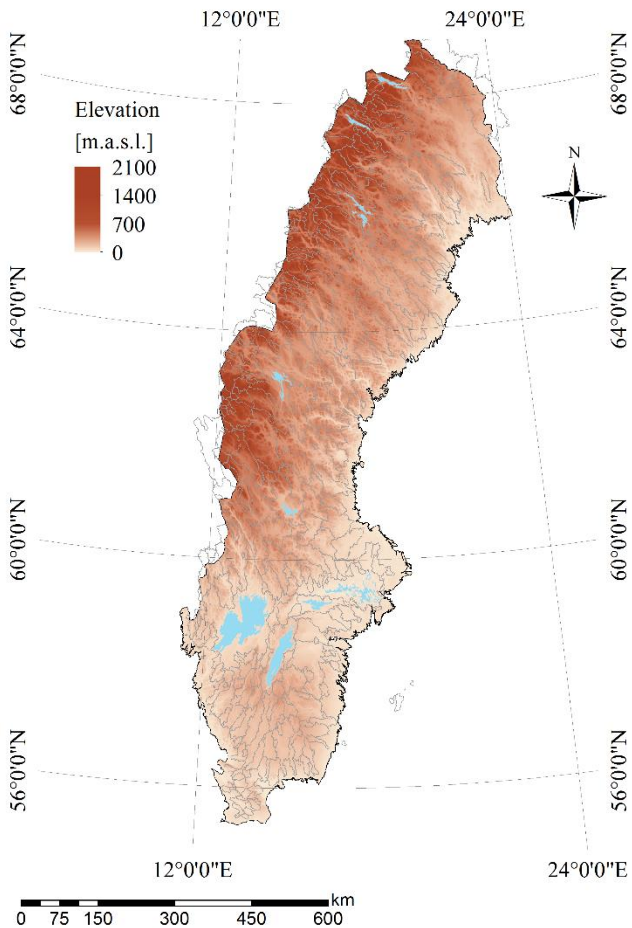

Figure 4 Map showing the elevation in meters above sea level (m a.s.l.). Data was obtained from the Swedish water archive SVAR (Eklund, 2011).

2.2. INDICES

The indices used in this study were the Standardized Precipitation Index (SPI), the Standardized Streamflow Index (SSI) and a threshold-based index (in the figures the threshold index is shortened to TH). Indices like the Palmer Drought Severity Index and Snow Water Supply Index (World Meteorological Organization, 2016) were not included because data for reservoir storage and the soil water-holding capacity were not available. The Standardized Precipitation Evaporation Index and the Standardized Snow Melt and Rain Index use precipitation and temperature to estimate streamflow (World Meteorological Organization, 2016), but since streamflow data was available for all the catchments the SSI was used instead. Below follows a more detailed description of the indices used in the study and how they were calculated.

2.2.1. Standardized Precipitation Index (SPI)

The SPI is based on the probability of precipitation computed from historical precipitation data on a timescale from one month or longer, but daily or weekly data could be used as well without changing the method. To compute the SPI a set of accumulation periods (from here on only mentioned as AP) is used, typically the 3, 6, 12, 24 and 48 months previous to the month of interest, to determine a value for each month, if using a monthly timescale, for all the years in the time series (McKee, Doesken and Kleist, 1993). The accumulated data is arranged into sets containing the values for each month for all years. Then a probability distribution is fitted to each monthly series to determine the relationship of probability to precipitation (McKee, Doesken and Kleist, 1993). For the SPI the gamma distribution is the preferable choice which has been proven to be effective when analyzing precipitation data (McKee, Doesken and Kleist, 1993; Stagge et al., 2015; Teutschbein and Seibert, 2012). With the probabilities determined, the inverse of the normal cumulative distribution is used to calculate the standardized precipitation deviation with the mean zero and standard deviation one. The resulting values are the SPI (McKee, Doesken and Kleist, 1993; Guttman, 1999). For the SPI values, the return period of one in 1000 is represented by the bounds ±3.09 and the return period of one in 100 by ±2.33. An extreme drought event can be said to correspond to values lower than -2 (Guttman, 1999), a full overview of the SPI values and the corresponding drought categories can be seen in Table 1. Droughts are identified by the SPI when the results are continuously negative and reach the value -1 and continues until it reaches 0 (McKee, Doesken and Kleist, 1993). A weakness of the model is that it does not account for the temperature, meaning that the index neglects evaporation and snow accumulation which can affect the occurrence of droughts in some climates. The SPI also uses a prior distribution which could be misinforming in some environments when examining short-duration events or the start and end of a drought (World Meteorological Organization, 2016).

Table 1 Drought definitions and corresponding SPI or SSI values as defined by McKee, Doesken and Kleist (1993)

SPI or SSI value	Drought category
$0 \geq SPI > -1$	Mild drought
$-1 \geq SPI > -1.5$	Moderate drought
$-1.5 \geq SPI > -2$	Severe drought
$-2 \geq SPI$	Extreme drought

Ideally time series should consist of a minimum of 30 years to make the distribution fitting robust. Changing the time scales, which is possible with SPI and the indices derived from it like the SSI, can be used to identify different types of droughts (Vicente-Serrano et al., 2010). SPI calculated with a 1-month AP is, mostly, related to short term conditions and to soil water deficit (Khan, Gabriel and Rana, 2008; World Meteorological Organization, 2012). Calculating the SPI over only one month might lead to large positive or negative values for the index despite only small divergences from the mean precipitation, therefore interpretation of these results must be done cautiously (World Meteorological Organization, 2012). SPI calculated with a 3-month AP can be used to estimate the seasonality of precipitation. When using a 6-month AP the SPI results are related to patterns in the precipitation on a seasonal or medium long timescale. The SPI computed over a 9-month AP can be related to inter-seasonal patterns in the precipitation taking place on an intermediate time scale. SPI calculated over a 12-month AP is associated with long-term patterns in precipitation and to changes in streamflow or reservoir and groundwater levels (Khan, Gabriel and Rana, 2008; World Meteorological Organization, 2012).

The SPI was calculated with a daily resolution using six different AP: 31, 61, 91, 183, 247 and 365 days corresponding to the commonly used 1, 2, 3, 6, 9 and 12 months AP. The accumulated precipitation was then arranged into series containing the values for each day of the year for all 30 years, resulting in 365 series with 30 accumulated values for each AP. The gamma distribution function was then fitted to each of these series to obtain the probabilities of precipitation. Zero precipitation, or streamflow, was handled by estimating the probability of zero precipitation, or streamflow, separately and then compute the probability of precipitation or streamflow:

$$p(0) = n(0)/(n + 1) \qquad (1)$$

$$p(x) = p(0) + (1-p(0))*cdf(x) \qquad (2)$$

Where p(0) is the probability of zero precipitation or streamflow, n(0) is the number of zero values, n is the total number of precipitation or streamflow values, p(x) is the probability of precipitation or streamflow and cdf(x) is the cumulative distribution function at a day with x millimeters of precipitation (Lloyed-Hughes and Saunders, 2002; Wu et al., 2007; Sienz et al., 2012; Stagge et al., 2015).The probabilities of precipitation were then normalized to obtain the SPI.

Both the SPI and the SSI use accumulated data and the longest AP used in this study was 12 months. This meant that the accumulated data series for the precipitation and the streamflow only contained 30 years, from October 1 1983 until September 30 2013.

2.2.2. Standardized Streamflow Index (SSI)

The SSI is calculated in the same way as the SPI by accumulating daily streamflow data before fitting probability distributions to obtain the probabilities which are then normalized to obtain the index (Telesca et al., 2012). However, unlike the SPI where the gamma probability distribution is recommended there is no probability distribution that has been proven to give a best fit for streamflow data for all types of catchments. This is because streamflow shows greater variability on a spatial scale, due to the influence of several factors such as topography and vegetation. This results in difficulties to choose the most appropriate distribution for the streamflow index due to variability in the probability distribution (Vicente-Serrano, et al., 2012). It is recommended to use different probability distributions for different gauging stations or months when calculating the SSI. However, if a single probability distribution is to be used then Vicente-Serrano et al. (2012) recommend the generalized extreme value or the log-logistic distribution. Therefore, five different probability distributions, the lognormal, loglogistic, generalized extreme value distribution, generalized Pareto and the Weibull distribution were tested for each series of daily values as suggested by Vicente-Serrano et al. (2012) and the distribution giving the best fit was chosen. The Two-sample Kolmogorov-Smirnov test, which determines the maximum discrepancy between the empirical data and the fitted distribution, was used to determine which probability distribution fitted the data best. If two or more distributions resulted in acceptable fits the mean square error was used as a second test to find the distribution giving the best fit among those. Figure A1 in Appendix A shows how often a distribution gave the best fit for each AP. Zero flow was handled in the same way as zero precipitation for the SPI (eq. 1 and 2). After the probabilities were obtained they were normalized to get the SSI.

2.2.3. Threshold index

The threshold index defines droughts when the streamflow falls below a predefined threshold which can be either fixed for the whole study period or vary with the timesteps. Thresholds in the range of the 70^{th} to the 90^{th} percentile are considered reasonable in perennial rivers (Hisdal et al., 2004). In regions with seasonal climate with snow accumulation it is important to consider snow-related processes when looking at drought development. Snow accumulation prevents recharge of groundwater and reduces streamflow until the snow melts (Van Loon, 2015). Using a variable threshold is the best way to account for seasonality in catchments with snow accumulation. The variable threshold can be calculated in different ways (Bayene et al., 2014). But the best way to reflect seasonality is a daily variable threshold based on the 80^{th} percentile of a moving window of 30 days (Van Loon and Laaha, 2015). The method was originally developed to use timesteps of one month or longer, but it has been used for daily timesteps too (Hisdal et al., 2004). Without very long time series smoothing of the thresholds is necessary to cancel out the variability which for example is suggested by Hisdal et al. (2004) and Beyene et al. (2014). Both Hisdal et al. (2004) and Beyene et al. (2014) use an n-window that moves through the time series so that the daily threshold is calculated for those n days in each year. The moving window method is recommended for most catchments but in particular for catchment with snow accumulation since it will help reduce artefact events that occur due to rapid snow melt (Beyene et al., 2014).

In this study thresholds were calculated on a daily scale as the 80^{th} percentile of the flow duration curve for a 30-day moving window. This was done until a threshold was obtained for all 365 days. Annual variation was accounted for by calculating the daily threshold for the ith 30-day window over all the years in the time period. The 30-day window was used to further smooth the thresholds as recommended by Van Loon and Laaha (2015).

2.3. DROUGHT EVENT ANALYSIS

2.3.1. Drought event definition

In this study the same definition of a drought event when using the SPI was used as defined by McKee, Doesken and Kleist (1993). The drought starts when the daily SPI values drops below zero and last until its zero or greater again after first having reached a value of minus one or less. The same way to define drought events was used for the SSI.

Using the threshold method a drought event starts when the daily streamflow is below the threshold for that day and continues until the streamflow is greater than the corresponding threshold. Computing the threshold method on a daily basis often results in longer drought events being divided into shorter droughts whenever the flow exceeds the threshold for a short time period (Hisdal et al., 2004). This problem can be solved by pooling together droughts that are separated by a certain number of days. Fleig et al. (2006) showed, by looking at the sensitivity curves when using different windows to pool droughts, that a maximum pooling was obtained using a window of 10 to 15 days, meaning that the characteristics did not change substantially with larger windows, although the sensitivity curves started to level off already when using a five-day window. A 10-day window was used in several reports (Tallaksen, Madsen and Clausen, 1997; Van Loon, 2013; Beyene et al., 2014) but other authors used a two-day window (Engeland, Hisdal and Frigessi, 2004) or six-day window (Tate and Freeman, 2000). In this report a 10-day window was used to minimize the occurrence of minor droughts that were dependent without including long periods of high flows in the drought events. This method is called the *inter-event time criterion* and is defined by Tallaksen, Madsen and Clausen (1997) as:

$$d_{pool} = d_i + d_{i+1} + t_i \qquad (3)$$

Where d_{pool} is the duration of the pooled drought event, d_i and d_{i+1} are the durations for two drought events separated by t_i days with streamflow exceeding the threshold.

A standard procedure when using the threshold method is to remove minor drought events lasting less than a certain number of days. Van Loon and Laaha (2015), Hisdal et al. (2004), Fleig et al (2006) used up to five days as the maximum duration of a minor drought. Beyene et al (2014) and Van Loon (2013) removed drought events that lasted less than 15 days. However, Kaznowska and Banasik (2011) defined droughts lasting up to 20 days as minor droughts. The authors have not discussed their definitions of minor droughts that they chose to remove. In this report minor droughts that were removed were those that lasted less than 10 days since that is in the middle of the range found in other reports. The removal of minor droughts was done after the pooling of drought events.

2.3.2. Drought event statistics and correlations

The SPI and the SSI were plotted over time according to the latitude of the stations to visualize the results over both space and time. The correlation between the SPI and the SSI was investigated by correlating the two indices using Kendall’s Tau against each other for each catchment. Kendall’s Tau shows the how strong the monotonic relationship is between two variables. Kendall’s Tau is resistant to extreme values and therefore useful when data is not normally distributed (Helsel and Hirsch, 2002), which is why the test was chosen for the correlation analyses in this study. To investigate any potential lag time between the precipitation and the streamflow six different lag periods were tested for all AP. The tested lag periods were: no-lag. 1-month, 2-months, 3-months, 6-months, 9-months and 12-months. Dettinger and Diaz (2000) found that the lag time between precipitation peaks and stream flow peaks commonly range between 0-3 months but with longer delays at higher altitudes. Similar lag periods were expected to be found between meteorological and hydrological drought events. The SSI was shifted so it started on the first day after the initial lag period, e.g. the SPI started on day 1 and the SSI on day 31 when looking at the shortest lag period. This was done to find which lag period resulted in the strongest correlation between the SPI and the SSI in all the catchments for each AP.

For each of the three indices the results were summarized by calculating two drought characteristics:

- the total number of drought events (NDE)
- the total number of cumulative drought days (TCD).

The NDE and the TCD were calculated over the whole 30-year period for each station. The NDE and the TCD for each hydrological year were also calculated for each station. If a drought event started in one hydrological year and carried on into the following hydrological year, when calculating the annual series, it was split into two events, one for each hydrological year.

The NDE and the TCD calculated with the SSI and the threshold index were then correlated to the different meteorological variables and catchment properties: mean elevation, latitude, mean precipitation over the whole period, catchment size and the percentage of bedrock, wetlands, forest, agriculture and the surface area of lakes and streams in the catchment areas as well as how regulated the catchment areas are. Correlations between the NDE and TCD calculated with the SPI and the land cover properties, the degree of regulation or the catchment size were not tested since these characteristics do not influence the precipitation over a catchment area. Correlation analyses were also done between the NDE and the TCD for each index with the other indices. All correlation analyses were done with Kendall's Tau using a significance level of $p < 0.05$.

In order to decrease the effect of the latitude on the correlations between the drought characteristics and the catchment properties, the catchments were divided into three groups according to the latitude (Fig. 5). One group consisted of the catchments in southern Sweden which was all catchments located below latitude 60. The catchments in central Sweden were those located between latitude 60 and 64. The last group consisted of the catchment in northern Sweden above latitude 64. The catchments were also divided according to the mean elevation of the catchment area into one mountainous group, catchments above 700 m a.s.l., and one lowland group, catchments below 700 m a.s.l. (Fig. 5). This was done to investigate if there were different catchment properties promoting droughts for different types of catchments.

The non-parametric Mann-Kendall test was used to analyze the annual NDE and TCD series for temporal trends for each catchment area and each index during the study period between 1983 and 2013. A significance level of $p < 0.05$ was used for the Mann-Kendall trend tests. The percentages of catchments with either significant positive or negative trends were calculated for each index and each AP.

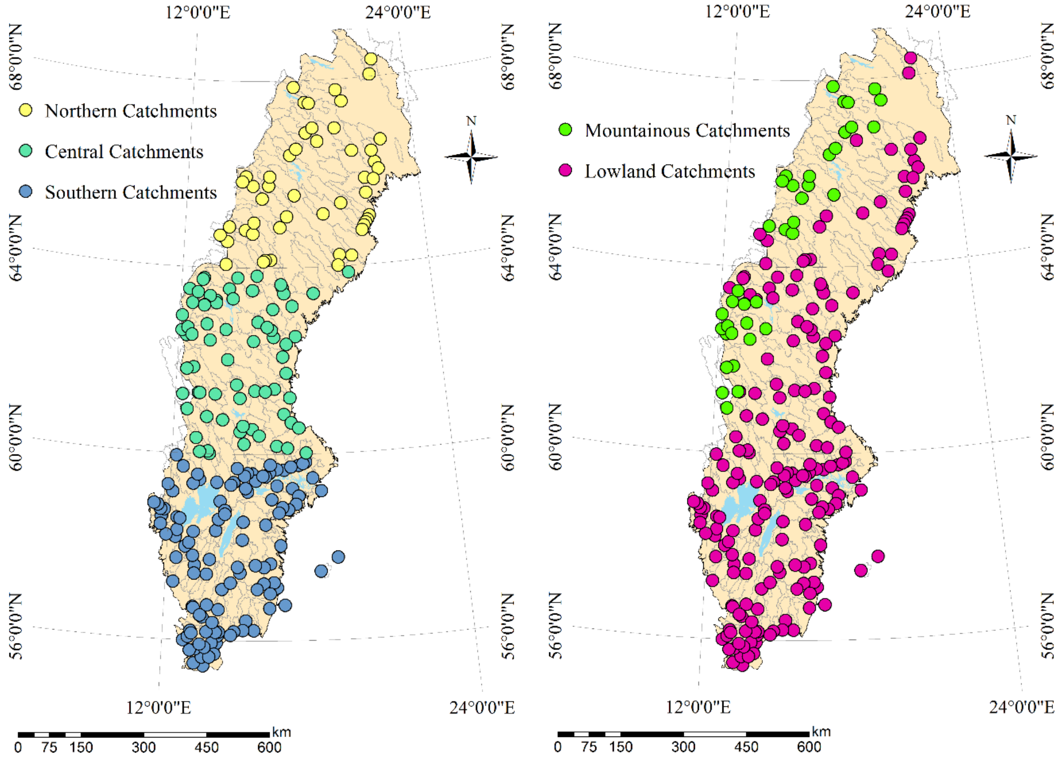

Figure 5 To the left: Locations of the streamflow gauging stations divided into northern (50 stations), central (70 stations) and southern Sweden (115 stations). To the right: Locations of the streamflow gauging stations divided into stations located in mountainous catchments (39 stations) and lowland catchments (196 stations). Data was obtained from the Swedish water archive SVAR (Eklund, 2011).

3. RESULTS

3.1. SPI AND SSI OVER TIME

When plotting the SPI and SSI over time with the catchments sorted after latitude along the vertical axis there were two noticeable features: firstly, the SPI and SSI followed the same pattern and secondly the events got more drawn out in time with longer AP. Looking at Figure 6 showing the SSI_{12} (SSI calculated with a 12-month AP) plotted over time it was possible to see some extensive drought events that occurred during the period of the study. There were especially two noticeable drought periods that affected the whole country with severe droughts (Table 1), from south to north, in the hydrological years of 1995-1996 and 2002-2003 (Fig. 6). Between 1989 and 1993 it appear to have been a prolonged period with dryer than normal conditions in central and southern Sweden. The period between 1989 and 1993 in central and southern Sweden contained mostly mild to moderate droughts. The two nationwide drought periods in 1995-1996 and 2002-2003 consisted, to a high degree, of severe or extreme drought events. The figures containing the SPI and the other SSI AP plotted over time can be found in Appendix A Figures A2-A12.

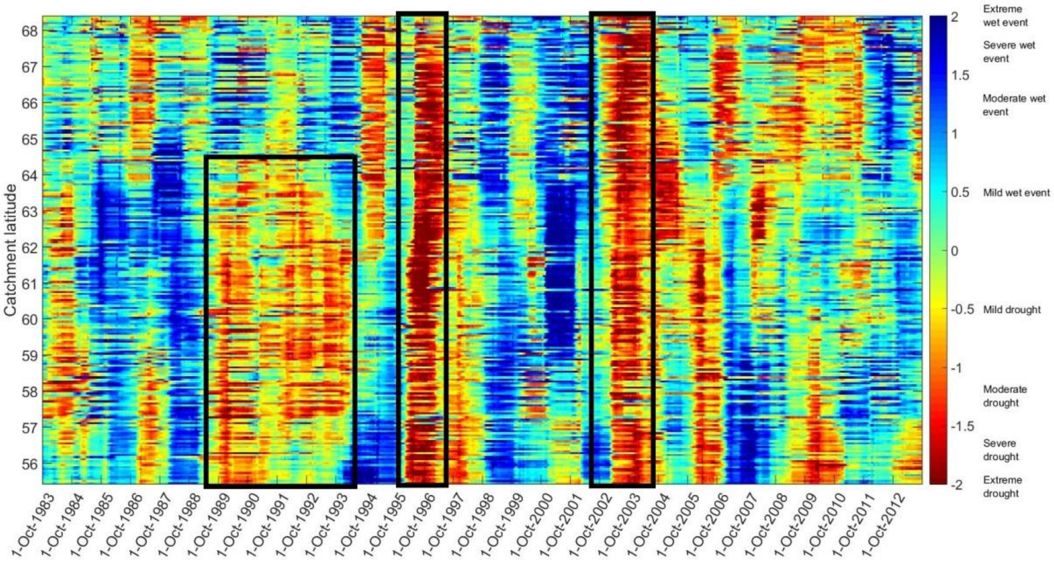

Figure 6 The SSI_{12} plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis. The drought events discussed in the text above are marked with black boxes to make them easier to see.

3.2. LAG AND TIME CORRELATION BETWEEN SPI AND SSI

In Figure 7 the percentage of times the different lag periods gave the strongest positive correlation between the SPI and the SSI is shown. The histograms (Fig. 7) show how often the different lag periods gave the strongest positive correlation between the two indices for each AP. The two indices were compared for each station using Kendall's Tau with a significance level of $p < 0.05$ and the lag period resulting in the most significant positive correlation values, τ, was chosen. See Figure 8 for an overview of the strongest positive correlation values for all stations. One month was the lag period that gave the strongest positive correlation between the two indices the most number of times for all AP. Another noticeable pattern was that the correlation increased, bigger τ, with the length of the AP (Fig. 8). For the 1-month AP the mean τ was 0.33 and for the 12-month AP the mean τ was 0.64.

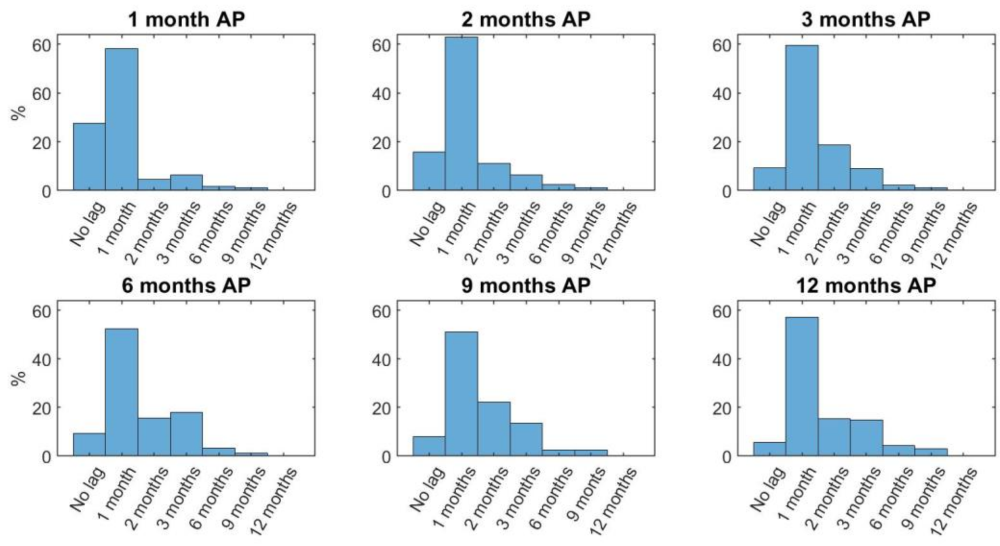

Figure 7 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for all 235 catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

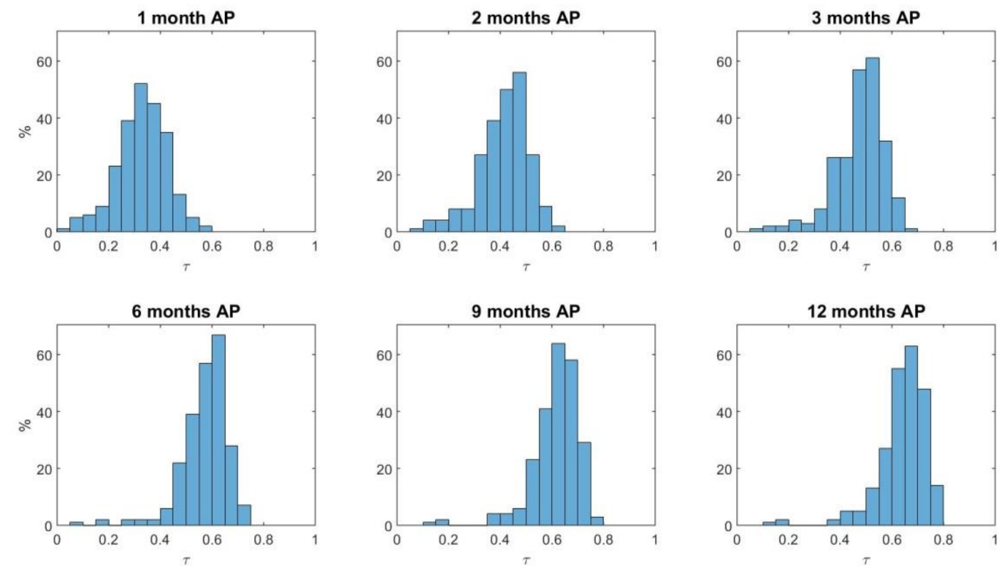

Figure 8 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for all 235 catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

In the lowland catchments the 1-month lag period for the SSI was the lag period that correlated strongest with the SPI most often for all AP (Fig. A13 in Appendix A). The same result was obtained for the mountainous catchments with the exception of the 6-months AP where the 3-months lag period gave the strongest correlation most often (Fig. A15 in Appendix A). For both mountainous and lowland catchments the correlations between the SPI and the SSI became more positive with longer AP (Fig. A14 and A16 in Appendix A).

The 1-month lag period also gave the strongest correlation between the SPI and the SSI for most of the catchments in all three parts when dividing Sweden according to latitude, apart from the 6-months AP in the north of Sweden where the 3-months lag period resulted in the most positive correlation most often, just like in the mountainous catchments (Fig. A17, A19 and A21 in Appendix A). The correlations also became more positive with longer AP for southern, central and northern Sweden (Fig. A18, A20 and A22 in Appendix A).

3.3. TRENDS FOR THE NUMBER OF DROUGHT EVENTS (NDE) AND THE TOTAL NUMBER OF CUMULATIVE DROUGHT DAYS (TCD)

For the majority of the catchments there were no significant ($p < 0.05$) trends for neither the NDE nor the TCD during the period 1983-2013 (Table 2). For the long-term SSI AP (9- and 12-month AP) and the threshold index there have been significant positive trends for the NDE and the TCD in between 7-12 % of the catchments. There were fewer catchments where there have been positive trends for the short-term SSI AP and for the SPI there were very few catchments with significant positive trends. For the SSI the percentage of catchments with positive trends increases with longer AP for both the NDE and the TCD. However, there were more stations with significant negative trends for the SPI than there were with significant positive trends, both for the NDE and the TCD. For the SSI there were more stations with significant negative trends for both the NDE and the TCD for the short-term AP (1-, 2- and 3-months AP) than there were with significant positive trends. For the long-term SSI AP there were more stations with significant positive trends than with significant negative trends.

Table 2 The table show the percentage of catchments of the total 235 catchments that show positive or negative significant ($p < 0.05$) trends for the NDE and the TCD for all the indices and AP, during the period 1983-2013. The trend analysis was done using the Mann-Kendall test

	Percentage of catchments with:			
Indices	Positive trends for the NDE	Negative trends for the NDE	Positive trends for the TCD	Negative trends for the TCD
SPI1	1.3 %	2.6 %	0.0 %	6.0 %
SPI2	0.0 %	3.0 %	0.0 %	7.2 %
SPI3	0.4 %	2.6 %	0.0 %	3.8 %
SPI6	0.0 %	6.4 %	0.0 %	2.1 %
SPI9	0.0 %	7.7 %	0.4 %	8.9 %
SPI12	1.7 %	14.5 %	2.6 %	9.8 %
SSI1	1.3 %	4.3 %	1.3 %	6.0 %
SSI2	0.9 %	6.0 %	2.6 %	3.8 %
SSI3	3.4 %	6.0 %	2.6 %	3.4 %
SSI6	3.8 %	3.0 %	4.3 %	3.0 %
SSI9	7.7 %	3.8 %	8.5 %	4.3 %
SSI12	8.9 %	5.1 %	11.5 %	5.5 %
TH	7.2 %	4.7 %	6.8 %	8.9 %

The locations of the streamflow gauging stations where significant positive or negative trends were observed during the time period of 1983 to 2013 for the different indices are shown in Figures 9-11. For the SSI and the SPI the trends for all the AP were grouped together.

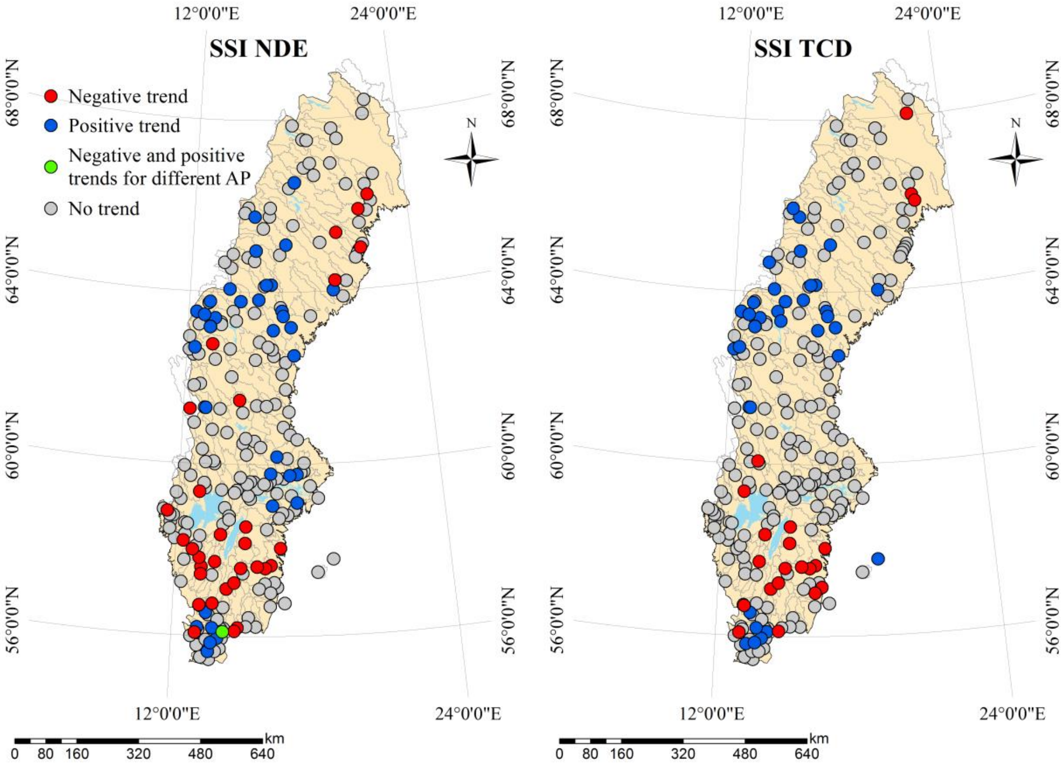

Figure 9 Map showing the streamflow gauging stations with significant ($p < 0.05$) positive trends (blue dots) or negative trends (red dots) for the NDE (to the left) and the TCD (to the right) for all SSI AP, between 1983 and 2013. For the NDE at one station (marked with a green dot), in Torsebro, there was a significant negative trend using the 2-month AP and a significant positive trend using the 9-month AP.

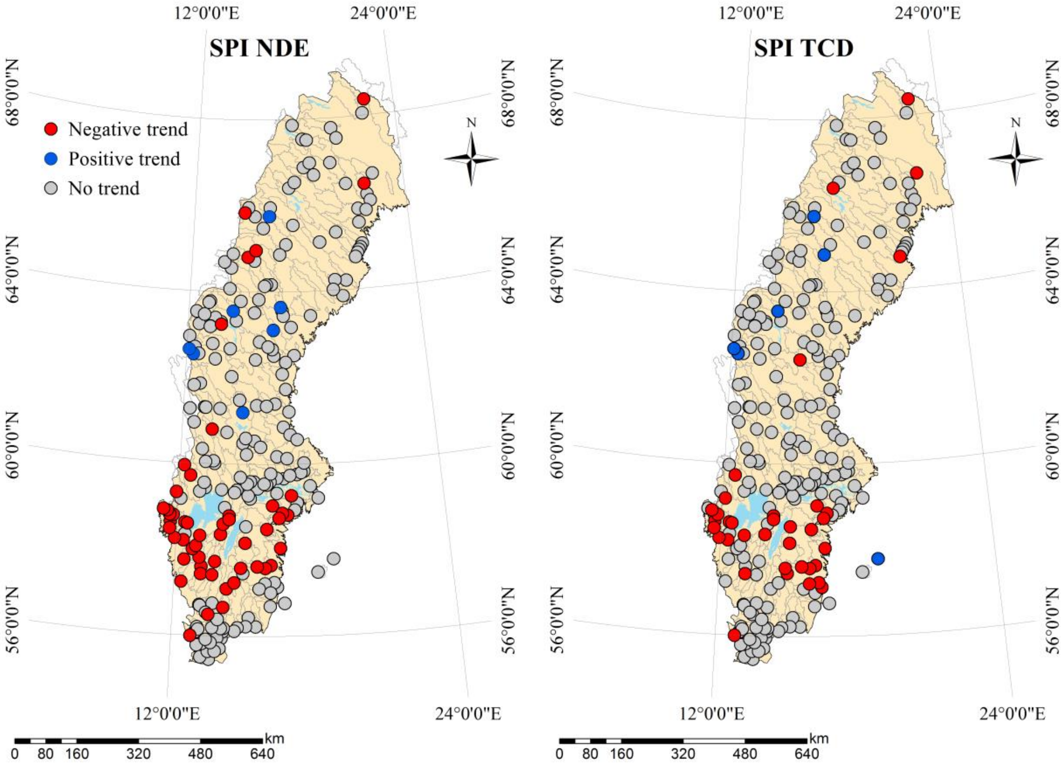

Figure 10 Map showing the streamflow gauging stations with significant ($p < 0.05$) positive trends (blue dots) or negative trends (red dots) for the NDE (to the left) and the TCD (to the right) for all SPI AP, between 1983 and 2013.

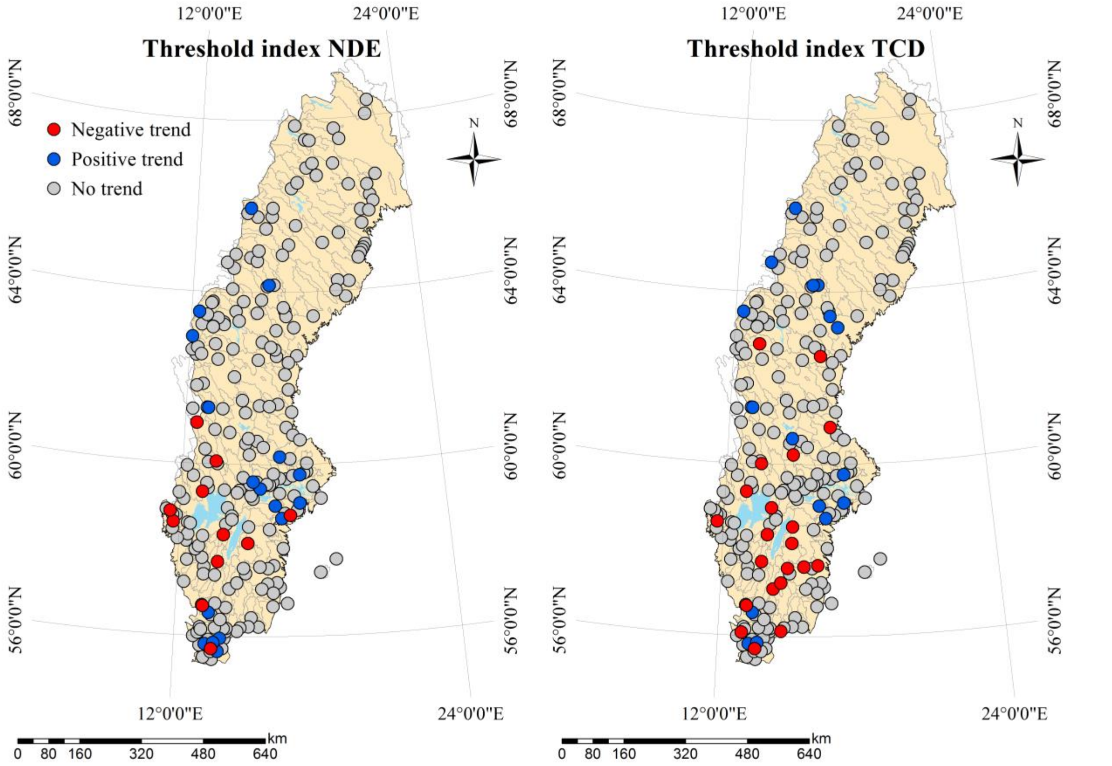

Figure 11 Map showing the streamflow gauging stations with significant ($p < 0.05$) positive trends (blue dots) or negative trends (red dots) for the NDE (to the left) and the TCD (to the right) calculated with the threshold index, between 1983 and 2013.

3.4. CORRELATION WITH METEOROLOGICAL VARIABLES AND CATCHMENT PROPERTIES

When looking at the correlations between drought indices for all stations and the catchment properties (Fig. 12) some patterns could be seen, however, there were no strong correlations ($\tau > 0.5$ or $\tau < -0.5$) for any index. Firstly, there were differences for how the drought characteristics for the indices correlated to the different variables. There were negative correlations between the NDE calculated with the SPI and latitude, mean elevation and mean precipitation while the NDE calculated with SSI and threshold index were positively correlated to the same variables, however, there were not significant correlations ($p < 0.05$) for all AP. For the TCD the correlations were the opposite for latitude, mean elevation and mean precipitation. There were some positive correlations between these variables and the TCD calculated with the SPI while the TCD calculated with the different SSI AP were negatively correlated to latitude and mean elevation, but still showed some positive correlations to the mean precipitation. Secondly the correlations between the drought characteristics calculated with the SSI and threshold index with many of the catchment properties differed between the NDE and the TCD.

Looking at mountainous catchments only (Fig. 13) there were fewer correlations over all. A noticeable difference was that most correlations between the drought characteristics calculated with the SPI and mean elevation were gone, there were also fewer correlations between the NDE calculated with the SPI and latitude and mean precipitation. For the SSI the most correlations between the TCD and the different meteorological variables and catchment properties were gone in the mountainous catchments.

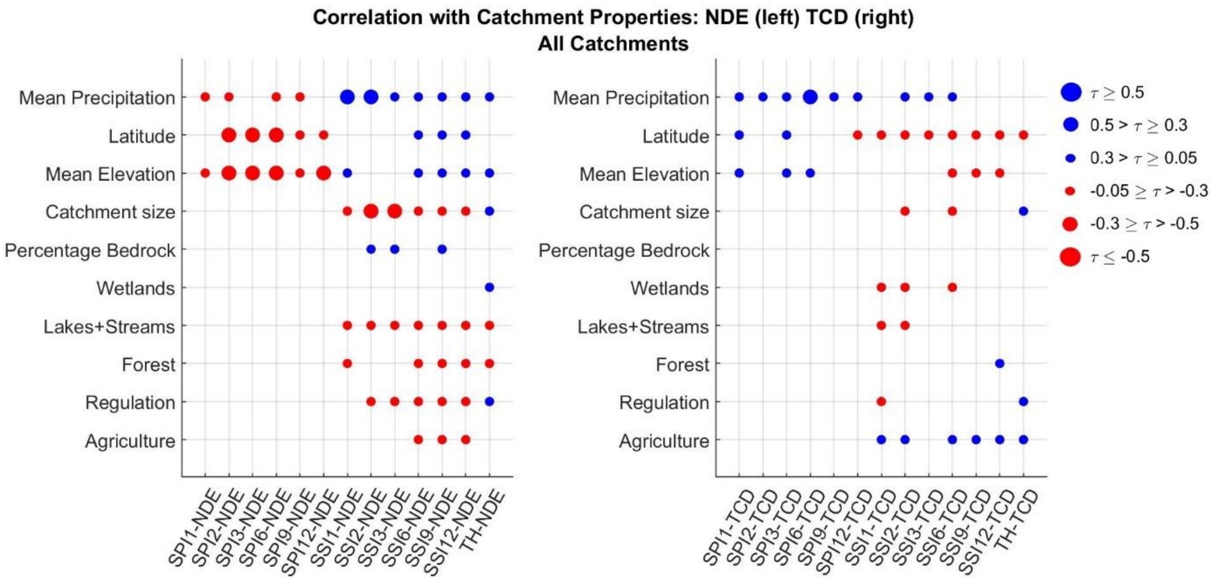

Figure 12 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for all 235 catchments, using Kendall’s Tau with a significance level of $p < 0.05$.

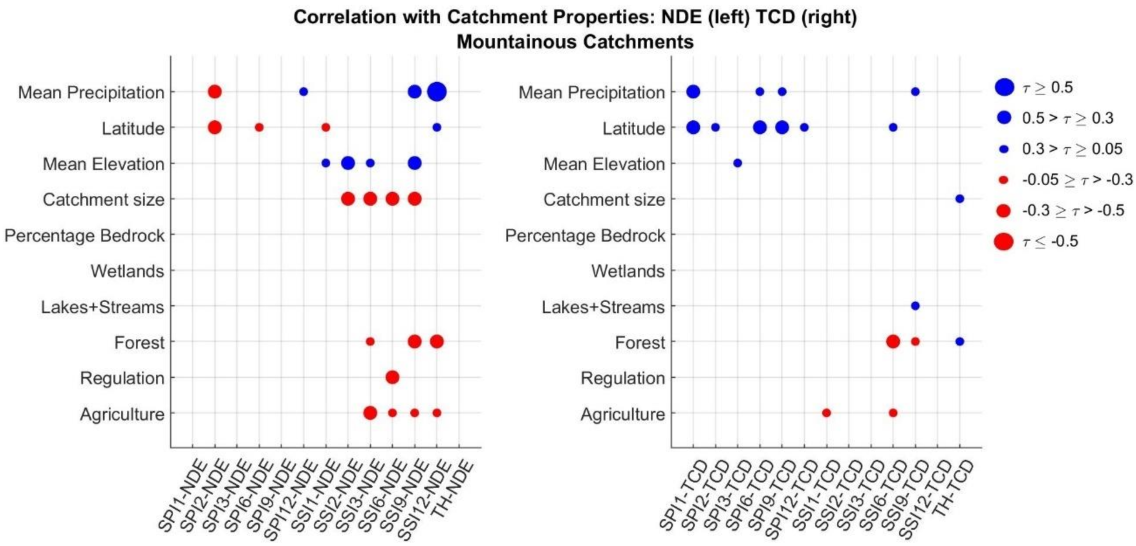

Figure 13 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for the 39 mountainous catchments, with a mean elevation > 700 m a.s.l, using Kendall’s Tau with a significance level of $p < 0.05$.

In the lowland catchments (Fig. 14) the correlations for the drought characteristics calculated with the SPI looked somewhat similar to those when looking at all catchments (Fig. 12). The correlations between the catchments properties and the TCD calculated with the SSI in the lowland catchments looked similar to those seen for all catchments, but for the NDE there were some differences between lowland catchments and all catchments, e.g. for latitude and mean elevation.

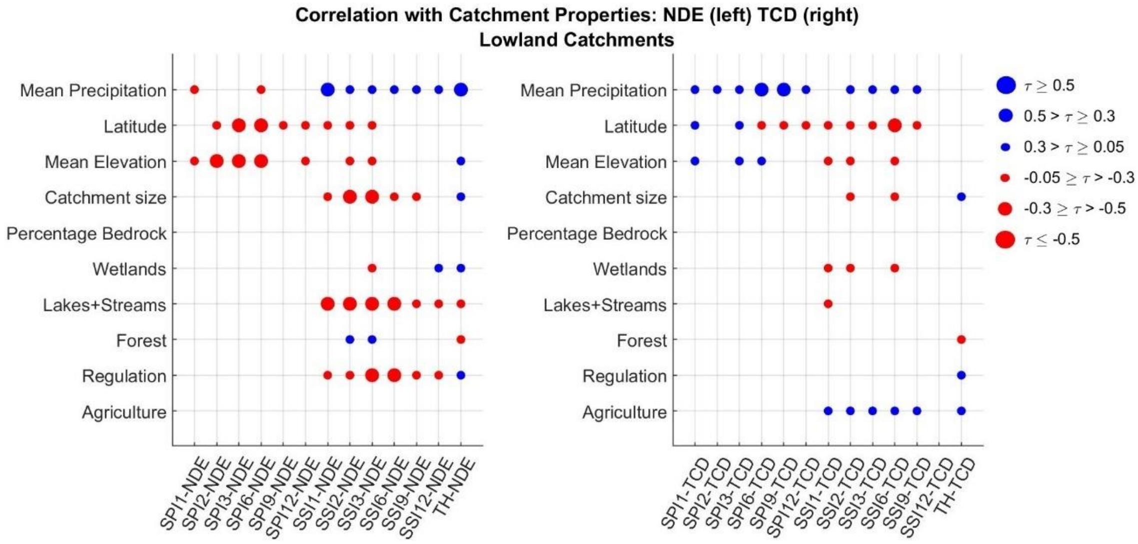

Figure 14 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for the 196 lowland catchments, with a mean elevation < 700 m a.s.l., using Kendall's Tau with a significance level of $p < 0.05$.

When dividing the catchments according to latitude into southern, central and northern Sweden (Fig. 15-17) there were some noticeable differences between the different parts of the country. In the north of Sweden there were no significant correlations between the latitude and the drought characteristics for the different indices (Fig. 15). The correlations with latitude and the drought characteristics calculated with the SSI and the threshold index were also mostly gone in central Sweden (Fig. 16). In central and northern Sweden the NDE calculated with the different SSI AP were positively correlated with mean elevation but in the south of Sweden these correlations were gone (Fig. 17). There were noticeable differences between the different parts of Sweden in how the drought characteristics calculated with the SSI and the threshold index correlated to the catchment properties. For example, northern Sweden was the only part where there were several significant correlations between the drought characteristics calculated with the SSI and the percentage of bedrock in the soil. Another example of these differences was the correlations with the amount wetlands in the catchment areas. In northern Sweden wetlands were negatively correlated to the drought characteristics calculated with the SSI, in central Sweden there were no significant correlations and in southern Sweden there were a few positive correlations with the NDE calculated with the SSI.

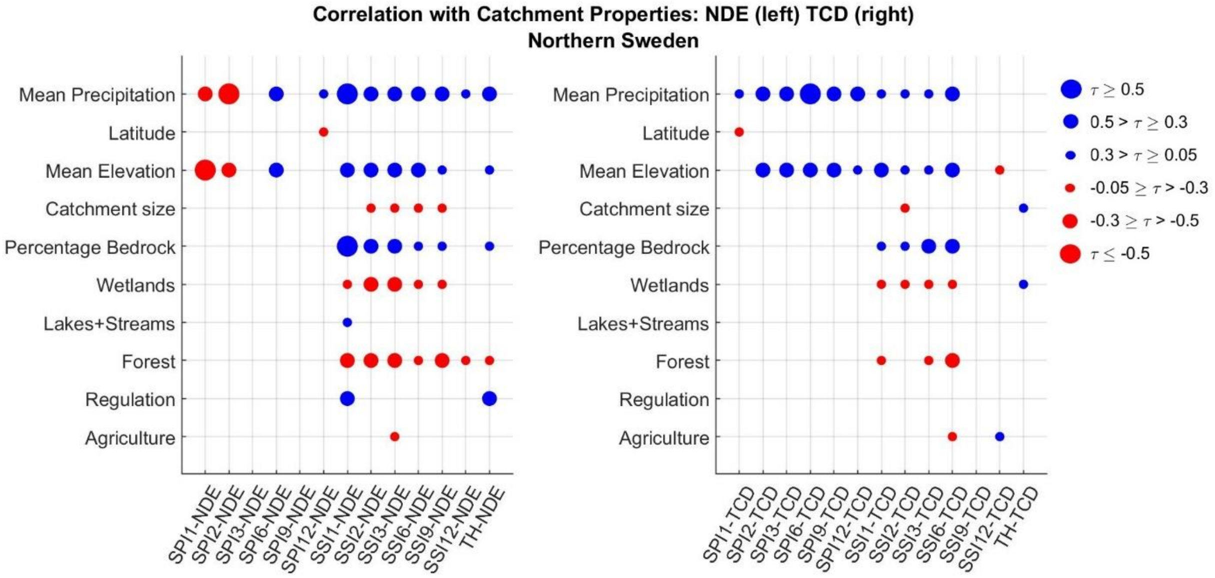

Figure 15 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for the 50 catchments in northern Sweden, located above latitude 64, using Kendall's Tau with a significance level of $p < 0.05$.

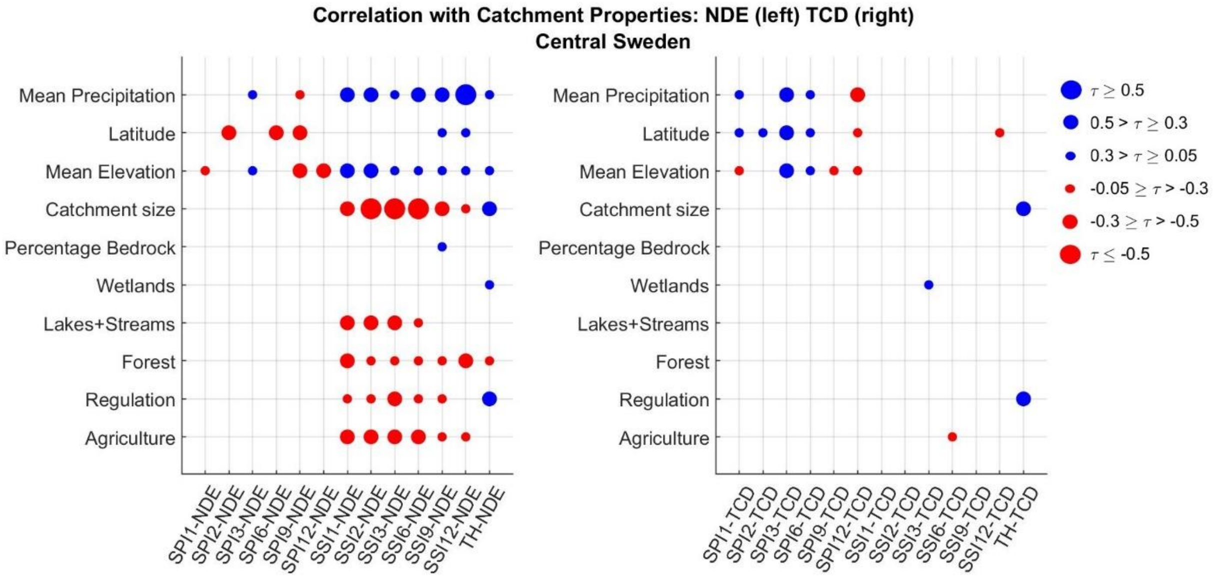

Figure 16 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for the 70 catchments in central Sweden, located between latitude 60 and 64, using Kendall's Tau with a significance level of $p < 0.05$.

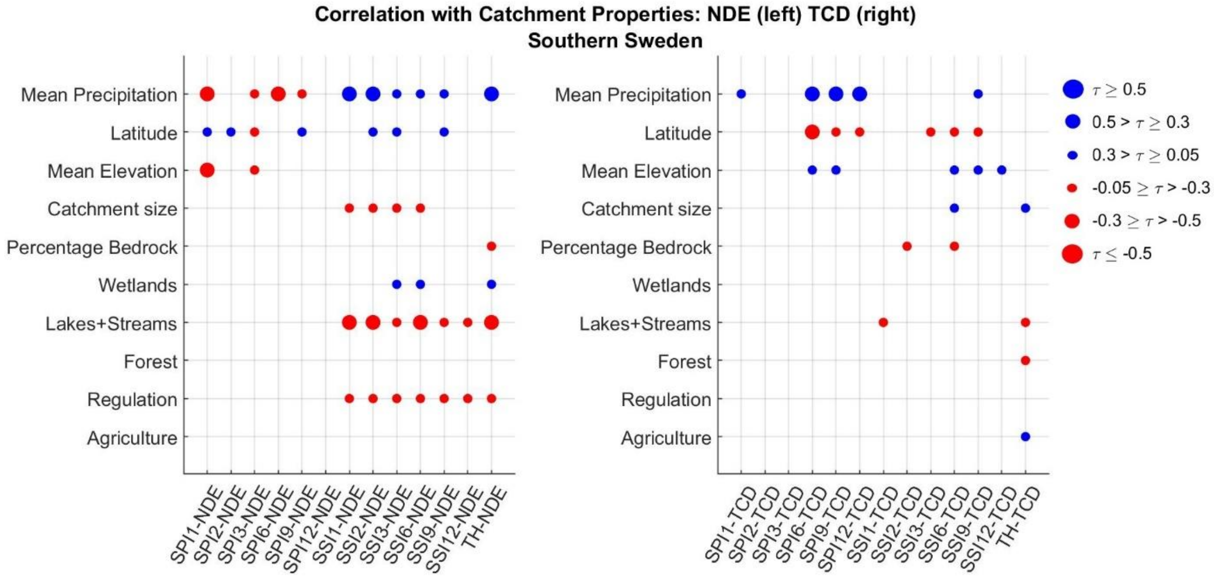

Figure 17 Correlations between the different catchment properties and the NDE (to the left) and TCD (to the right) calculated with the SPI, SSI and threshold index for the 115 catchments in southern Sweden, located below latitude 60, using Kendall's Tau with a significance level of $p < 0.05$.

3.5. CORRELATION BETWEEN THE INDICES FOR THE NUMBER OF DROUGHT EVENTS (NDE) AND THE TOTAL NUMBER OF CUMULATIVE DROUGHT DAYS (TCD)

The correlations between the NDE calculated with the SPI and the SSI were positive for different AP of the same index, e.g. the SSI_1-NDE was positively correlated to the NDE for the other SSI AP (Fig. 18). The correlations were stronger for the SSI than the SPI. Between the NDE calculated with the SSI and the SPI there were not many significant correlations at all, a few weak negative correlations. The correlations between the TCD for the different indices were fewer and weaker among the different AP for the same index, on the other hand there were more significant positive correlations between the TCD calculated with the SSI and the SPI, especially for the SPI with longer AP, than for the NDE (Fig. 18).

For the lowland catchments (Fig. 19) the correlations between the drought characteristics for the different indices look similar to those for all catchments (Fig. 18) except that there were a few more significant positive correlations between the NDE calculated with the SSI and the SPI. For the mountainous catchments (Fig. 20) there were almost no significant correlations for the NDE calculated with the SPI. For the SSI there were positive correlations for the NDE but mainly for neighboring SSI AP, e.g. SSI_2-NDE with SSI_1-NDE and SSI_3-NDE. For the TCD the correlations for the different SPI AP looked similar to the lowland catchments but with stronger positive correlations, more $0.5 > \tau \geq 0.3$ rather than $0.3 > \tau \geq 0.05$. For the SSI the correlations between the TCD for the different AP were almost exclusively with neighboring AP.

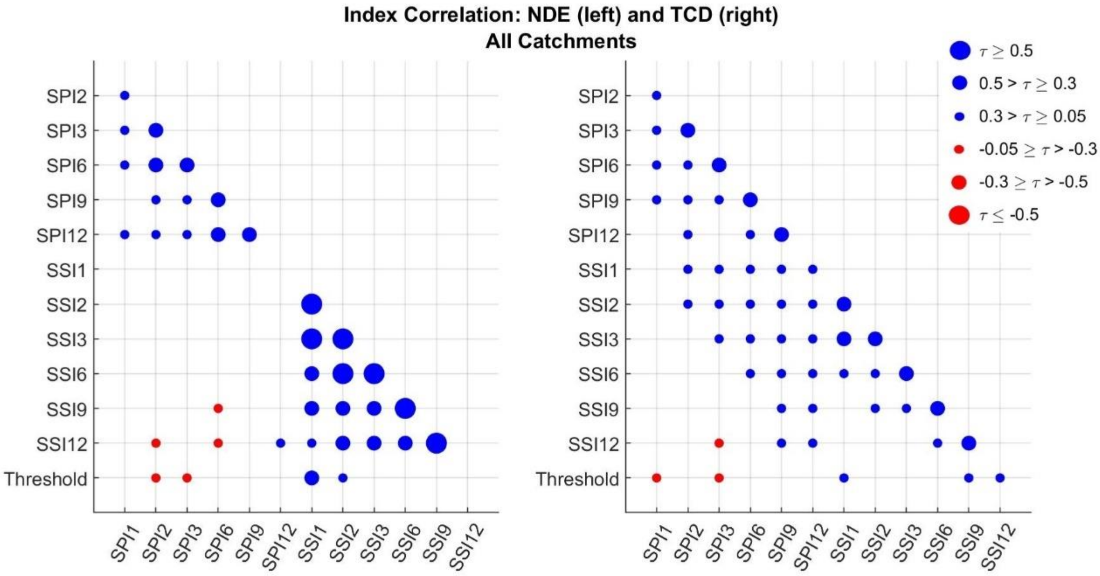

Figure 18 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for all 235 catchments, using Kendall's Tau with a significance level of $p < 0.05$.

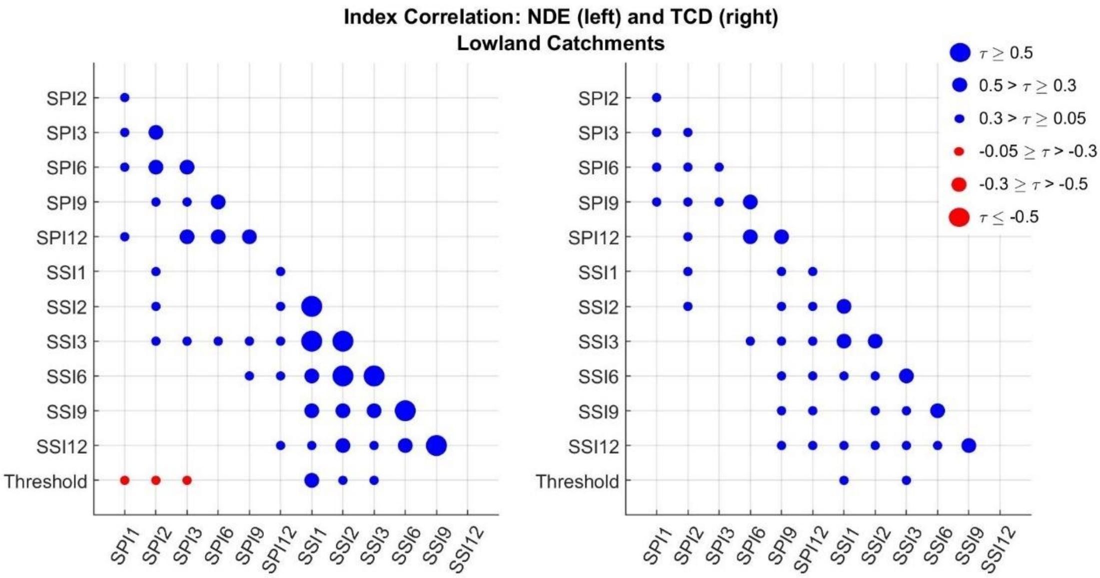

Figure 19 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for the 196 lowland catchments, with a mean elevation < 700 m a.s.l., using Kendall's Tau with a significance level of $p < 0.05$.

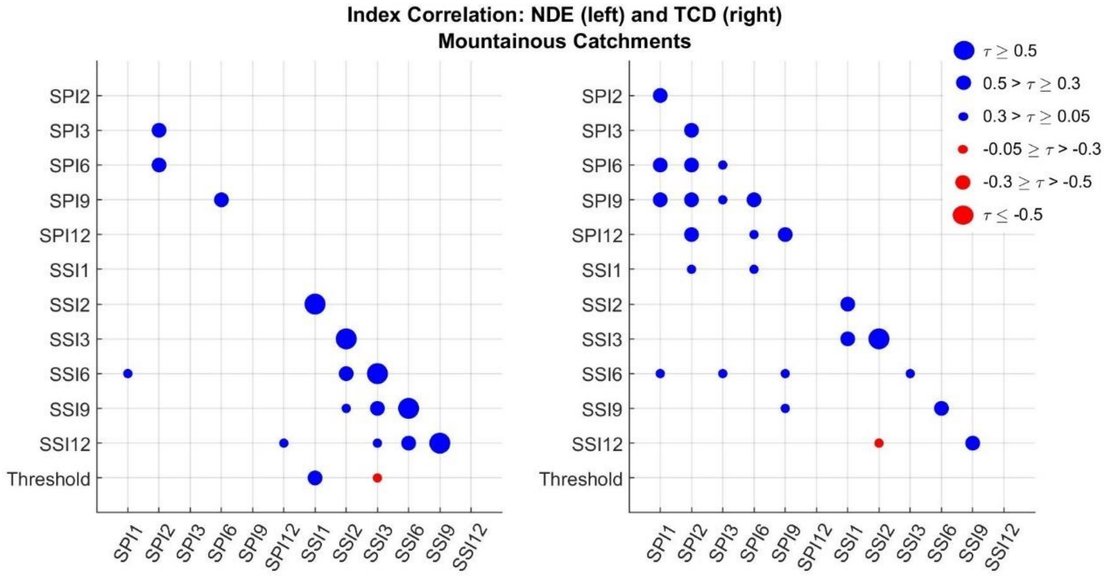

Figure 20 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for the 39 mountainous catchments, with a mean elevation > 700 m a.s.l., using Kendall's Tau with a significance level of $p < 0.05$.

The correlations for the drought characteristics between the different indices and AP with the catchments grouped after latitude (Fig. 21-23) showed both similarities and differences between the different parts of the country. In all parts, northern, central and southern Sweden, there were positive correlations between the NDE for the different SSI AP. Another similarity between the different parts of Sweden was positive correlations between the TCD for neighboring AP for the SSI. For the SPI the correlations between the TCD for the different AP looked similar in northern and southern Sweden. The NDE correlations for the SPI AP were different in the different parts. The correlations between the drought characteristics for the SPI and the SSI differed between the three parts of Sweden. In northern Sweden SPI_1-NDE and SPI_2-NDE were negatively correlated to the NDE calculated with the different SSI AP while there were positive correlations between the NDE calculated with the short term SPI AP (1 to 3 months AP) and the NDE calculated with the SSI in central Sweden.

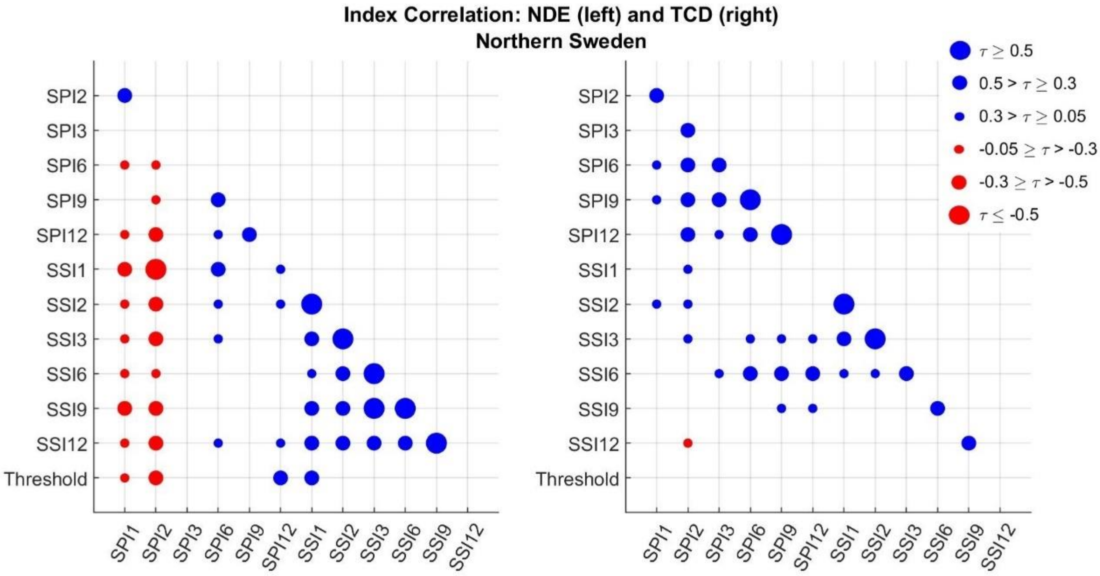

Figure 21 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for the 50 catchments in northern Sweden, located above latitude 64, using Kendall's Tau with a significance level of $p < 0.05$.

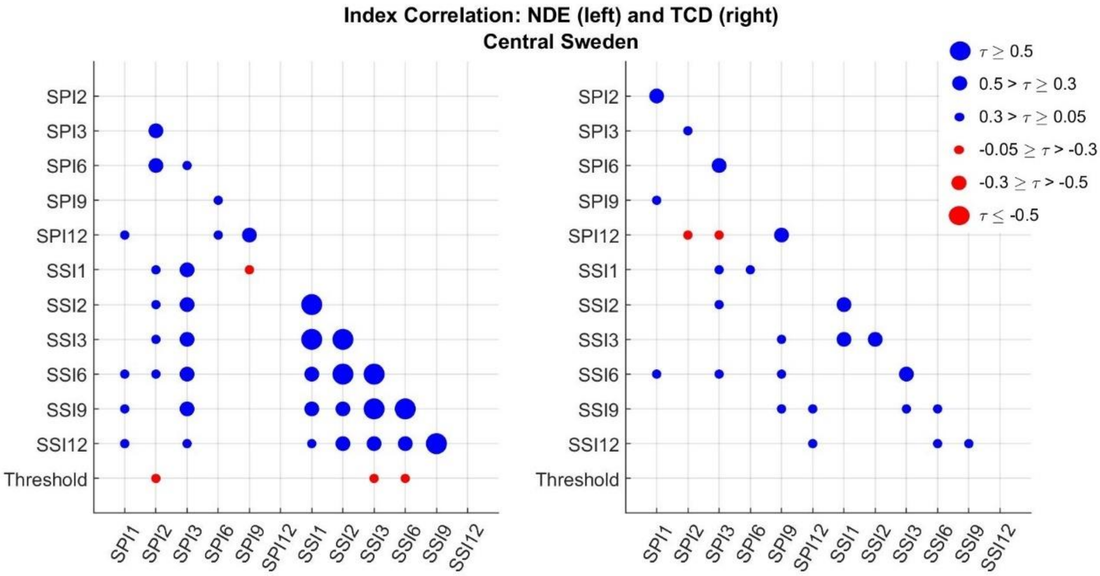

Figure 22 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for the 70 catchments in central Sweden, located between latitude 60 and 64, using Kendall's Tau with a significance level of $p < 0.05$.

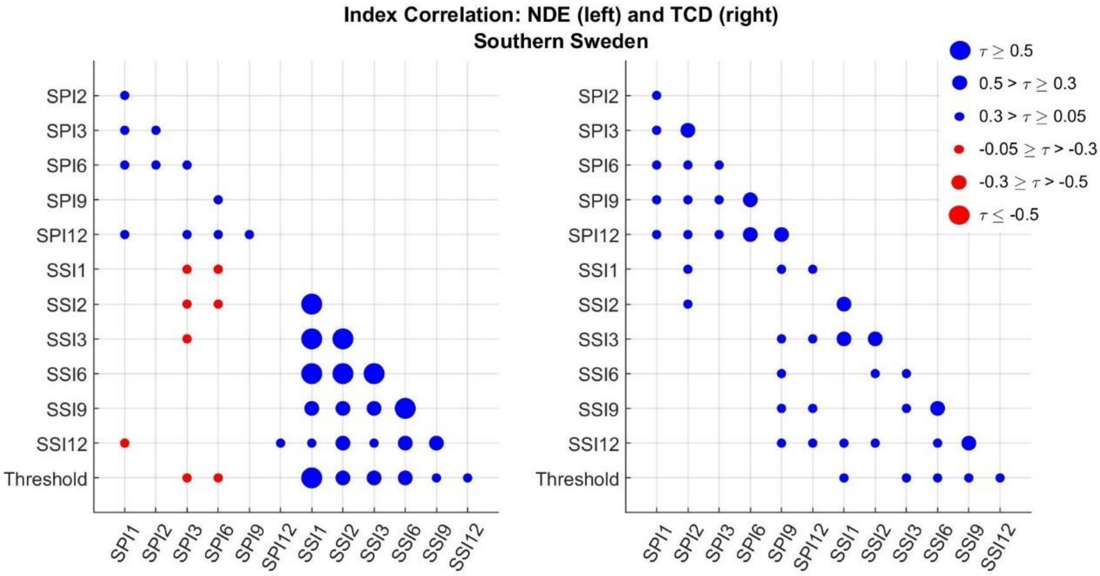

Figure 23 Correlations for the NDE (to the left) and the TCD (to the right) between the SPI, SSI and the threshold index for the 115 catchments in southern Sweden, located below latitude 60, using Kendall's Tau with a significance level of $p < 0.05$.

4. DISCUSSION

4.1. HISTORICAL DROUGHT ANALYSIS AND LAG BETWEEN SPI AND SSI

In Figure 6 it is possible to see nationwide droughts in the hydrological years of 1995-1996 and 2002-2003. According to SMHI 1996 was a year with an unusually low annual run off compared to the mean for the period 1961-2002 (Swedish Meteorological and Hydrological Institute, 2003) and in 2002 Radio Sweden reported that there were droughts in several parts of the country (Radio Sweden, 2002). This suggests that the SPI and SSI show drought events that coincide with real droughts. In the south and central parts there was a period between 1988/1989-1993 with below normal precipitation and streamflow which is shown as a moderate drought event in the figures. However, in northern Sweden there were no drought events during that period except for the summer of 1991. There are more examples of differences between the different parts of the country, for example in 1986/1987 there were drought events in the south and north of Sweden while in the central parts it was still relatively wet. These differences show a spatial variability in the drought event pattern during this period depending on the latitude. The drought pattern appears to differ between the south, central and north parts of the country but staying somewhat homogenous within the parts. A possible explanation is differences in climate and in the lengths of the seasons that exist between the different parts of the country with longer winter seasons in the north of Sweden and in the mountains (Swedish Meteorological and Hydrological Institute, 2009). The land use also differs between the different parts of the country (Fig. 3) with most of the agriculture located in southern Sweden and most of the wetlands in northern Sweden for example, which could be a contributing factor to the different patterns observed in the different parts of the country.

It is apparent that both the SPI and the SSI followed a similar pattern over time when looking at the indices plotted for the whole period (Fig. 6). It becomes more visible for the longer AP but for the extensive drought events it was possible to see the similarities for the shorter AP too. That the SPI and the SSI followed the same pattern over time was supported by the time correlation analysis between the two indices. The results from the time correlation analysis showed that the SSI correlated strongly with the SPI (mean $\tau > 0.5$) for the longer AP when taking into account a lag period between them. Of the tested lag periods the 1-month lag period was the one that most frequently gave the strongest positive correlation for all AP. The 1-month lag period also gave the strongest positive correlation when dividing the catchments into mountainous and lowland catchments as well as according to latitude into southern, central and northern Sweden. The strength of the correlations increased with the AP in all the cases (Fig. 8 and A13-A22 in Appendix A), for the one-year AP the majority of the correlations were with a τ somewhere between 0.5 and 0.8 which indicate a quite strong correlation between the SPI and the SSI. The result showing increasing correlations between the SPI and the SSI with longer AP is in line with the suggestion by WMO (2016) that AP of 12 months or longer might be the most useful choice when estimating hydrological impacts with the SPI. It is also supported by the fact that 12 months or longer are the SPI AP that relate best to changes in streamflow or reservoir and groundwater levels (Khan, Gabriel and Rana, 2008; World Meteorological Organization, 2012). This suggests that it would be possible to use precipitation data and apply a 1-month lag to predict hydrological streamflow droughts with some accuracy for longer AP in all parts of Sweden. At least it shows it is an option in those cases when reliable streamflow data is not available. It also shows that it takes some time for the propagation of a meteorological drought into a hydrological drought and in general it would take about one month or less for the drought propagation to happen in Swedish catchments. The 1-month lag period fall into the range of 0-3 months found by Dettinger and Diaz (2000) to be the lag times most commonly occurring between peak precipitation and peak streamflow. Compared to what Stefan et al. (2004) found to be the general lag time between precipitation variations and streamflow variations over the whole year in southern Romania, 2-3 months, the result for Sweden is a bit shorter and more in range with the lag period they found for the summer months, 0-1 month (Stefan et al., 2004). It is worth noticing that the no-lag result in this study does not necessarily mean that there is no lag, just that it is shorter than one month. With a finer resolution it would be possible to see if there was some lag period between the no lag and the 1-month lag resulting in stronger positive correlations between the SPI and the SSI. Due to time constraints it was not possible to try more lag periods between the 1-month lag period and the no-lag after the results were obtained and the possibility of a shorter lag period resulting in a stronger positive correlation between the SPI and the SSI was discovered. In the north of Sweden and in the mountainous catchments there was a departure from the general pattern for the 6-months AP where the SPI and the SSI correlated best with a 3-month lag period. An explanation for this could be the snow accumulation, which can be expected to be more prominent in the north and the mountains due to longer winters (Swedish Meteorological and Hydrological Institute, 2009). Snow accumulation delays the time it takes for the precipitation to reach the streams thus prolonging the lag period between the SPI and the SSI. There was also a pattern where longer lag periods were resulting in the strongest positive correlation more frequently in northern Sweden and in mountainous catchments, especially for the longer AP, but still less often than the 1-month lag period. The same phenomenon with longer lag periods between precipitation peaks and stream flow peaks in mountainous areas and at high latitudes was also observed by Dettinger and Diaz (2000).

4.2. TRENDS FOR THE NUMBER OF DROUGHT EVENTS (NDE) AND THE TOTAL NUMBER OF CUMULATIVE DROUGHT DAYS (TCD)

In the majority of the 235 catchments there had not been any significant increase or decrease in the NDE or in the TCD between 1983 and 2013 for any index (Table 2). This is supported by Wilson, Hisdal and Lawrene (2010) who looked at trends in the hydrological drought severity in the Nordic countries for three different time periods, 1920-2005, 1941-2005 and 1961-2000. They found that there were no significant trends in the drought severity for a majority of the streamflow gauging stations they used in their study for all three periods. The fact the trend results in this study are supported by other results from different periods reduces the risk of them just being a consequence of the chosen time interval.

In about 2-10 % of the catchments there were negative trends for both the TCD and the NDE calculated with the SPI. These trends were mainly located in a belt stretching over the central parts of southern Sweden (Fig. 10). This indicates a trend towards fewer and shorter meteorological droughts during the 30-year study period in this area in southern Sweden. For the longer SSI AP there were more catchments with significant positive trends than with negative trends for both the TCD and the NDE. For the shorter SSI AP the pattern was reversed with more catchment areas with observed significant negative trends, however, there were relatively few catchment areas with significant trends, positive or negative, for the shorter SSI AP. Most of the negative trends for the NDE and the TCD calculated with the SSI were located in the same area in the central parts of southern Sweden (Fig. 9) as seen for the SPI. Thus the trends with fewer and shorter meteorological droughts can be spatially connected to fewer and shorter hydrological droughts. As most hydrological droughts start with meteorological droughts (Van Loon, 2015) this result is not very surprising. Most of the streamflow gauging stations where positive trends have been observed for the NDE and the TCD calculated with the SSI are located in Skåne in southern Sweden or in an area roughly corresponding to Jämtland and Ångermanland in the northern parts of central Sweden and the very southern parts of northern Sweden (Fig. 9). There is also an area around Mälaren, Sweden’s third largest lake, with streamflow gauging stations where significant positive trends were observed for the NDE calculated with the SSI. These areas are roughly the same as those where significant positive trends were observed for the TCD and the NDE calculated with the threshold index (Fig. 11). Several of the streamflow gauging stations with significant negative trends observed for the drought characteristics calculated with the threshold index were located in the area in southern Sweden where negative trends were observed for the drought characteristics calculated with the SPI and the SSI. A similar spatial distribution of positive or negative trends was not visible compared to the report by Wilson, Hisdal and Lawrene (2010) which might be explained by the much smaller number of streamflow gauging stations located in Sweden in their report or by the different time periods.

Overall, it is possible to see that hydrological droughts became more common in some areas while there were other areas where both hydrological and meteorological droughts became fewer during 1983-2013. However, in most parts of the country there have not been any significant changes in the occurrence of neither hydrological nor meteorological drought events.

4.3. CORRELATION WITH CATCHMENT PROPERTIES

The SPI and the two streamflow indices, the SSI and the threshold index, showed several differences in how they correlated with the different catchment properties. But there were also differences between the AP for the same index. It can be expected that catchment properties correlate differently with changes in precipitation and streamflow. Elevation and latitude are characteristics that, apart from affecting the precipitation or snow accumulation directly, also affect land cover properties which then have effects on the streamflow and therefore on the SSI and the threshold index. The differences between the AP for the same index were probably because the different AP can be used to predict different types of droughts as discussed in 2.2.1. SPI calculated over a 1-month AP can be related to monthly precipitation patterns and to soil moisture fluctuations. The 3- and 6-months SPI can be related to seasonal precipitation patters while the 9-months SPI give an indication of inter-seasonal patterns. The 12-month SPI can be related to changes in streamflow or reservoir and groundwater levels (Khan, Gabriel and Rana, 2008; World Meteorological Organization, 2012).

For many catchment properties there was a pattern where the NDE and the TCD were correlated to them with different signs (e.g. Fig. 12). When the NDE was negatively correlated and the TCD correlation was positive it meant that an increase in that catchment property resulted in fewer drought events that could be separated in time but instead the drought events that occurred lasted longer which results in more drought days during the whole period, thus the positive TCD correlation. When the opposite occurred, positive NDE and negative TCD correlation, it is because there were more short drought events but less drought days in total as that catchment property increased. Longer, continuous winters, instead of winters where the temperature is pending around 0˚C, is one possible explanation for the phenomenon where a catchment property was correlated to fewer but longer droughts for the SSI or the threshold index.

4.3.1. Catchment correlations with the drought characteristics calculated with the SPI

For the SPI there were mostly negative correlations for the NDE and mostly positive correlations for the TCD with mean precipitation and mean elevation for all the different grouping of catchments (Fig. 12-17). The correlations between latitude and the drought characteristics for the SPI were more dependent on how the catchments were grouped. The correlations between the SPI and latitude and elevation when looking at all the catchments grouped together (Fig. 12) showed that there were fewer but longer droughts with increasing latitude and elevation for the shorter AP. If the NDE decreases while the TCD increases then there are more drought days in total but during fewer drought events meaning that the drought events last longer. When looking at the longer AP the droughts were fewer and shorter the further north in the country and the higher up one goes. The similarities might be because there was a significant correlation between the latitude and the mean elevation ($\tau = 0.50$). The similarities between the correlation for latitude and mean elevation with the SPI were also apparent in the lowland catchments (Fig. 14), less profound though, but the correlation between the latitude and mean elevation remained as well ($\tau = 0.48$). This makes it difficult to say which of the two factors was the one promoting fewer but longer droughts. In the mountainous catchments however, the correlation between the SPI and mean elevation was gone but there were still positive correlations between the TCD and latitude and some negative correlations with the NDE and latitude (Fig. 13). In the mountainous catchments the latitude seemed to be the most influencing factor. In the north of Sweden elevation was the most influencing characteristic along with the mean precipitation (Fig. 15). For the shorter AP, increasing elevation resulted in fewer but longer droughts while for the longer AP increased elevation led to more and longer droughts. A higher precipitation seasonality in mountainous catchments can be expected (Weingartner et al., 2013) which could explain the difference between long and short AP. The mean precipitation appeared to be negatively correlated to the NDE but positively correlated to the TCD for all the groupings of catchments but especially when looking at all the catchments grouped together (Fig. 12). A high mean precipitation would thus lead to fewer but longer droughts. In northern Sweden, particularly, the correlations with the mean precipitation were strong but for the longer AP, SPI_6 and SPI_{12}, it correlated positively with the NDE too. That a higher mean precipitation would promote longer droughts is counter-intuitive. However, the droughts were determined relatively and it is possible that some very wet events would lead to skewed probability distributions that would result in more days with precipitation falling below the “normal” conditions.

4.3.2. Catchment correlations with the drought characteristics calculated with the SSI and the threshold index

Correlations between the streamflow indices, the SSI and the threshold index, and the catchment properties varied quite a lot depending on how the catchments were grouped. When looking at all catchments grouped together the latitude was positively correlated to the NDE for the longer AP and negatively to the TCD which indicates that there were more short drought events but less drought days in total the further north one goes in Sweden (Fig. 12). This goes against the reasoning that longer winters, which could be expected in the north (Swedish Meteorological and Hydrological Institute, 2009), would lead to fewer but longer drought events. But these counter-intuitive correlations between latitude and the drought events might be due to the fact that in this study winter and summer droughts were not separated, also there might be different driving variables in different parts of the country (for example differences in land cover properties between the different parts with most agriculture in the south and the majority of wetlands located in the north of Sweden, see Figure 3) that overshadow this relationship. As pointed out in 3.4 there were few correlations between the SSI and latitude as well as between the threshold index and latitude when looking separately at each part of Sweden divided according to latitude (Fig. 15-17). This shows that on a smaller scale, at least within the central or northern part of Sweden there was no correlation between the latitude and the streamflow drought sensitivity. In the south of Sweden there was a correlation pattern indicating more but shorter droughts with increased latitude. On a larger scale, if the mountainous catchments were excluded, there was a negative correlation to latitude which means less and shorter hydrological droughts were to be expected the further north one goes when looking at the whole country.

Catchment size was negatively correlated to the NDE calculated with the SSI for all parts of Sweden and for both mountainous and lowland catchments (Fig. 12-17), but it showed some positive correlations to the threshold index. Over all, larger catchment areas seemed to be less drought-sensitive when using the SSI. This result is in line with what Van Loon and Laaha (2015) found to be the case for Austrian catchments with shorter drought durations in bigger catchments. An explanation could be that larger catchments could be expected to have a smoother streamflow regime over the year thus leading to less days falling into the drought category.

The percentage of bedrock, which gives an indication of the groundwater storage capacity in the catchment areas, only showed several significant correlations to the drought characteristics in northern Sweden (Fig. 15). There it was positively correlated to both the TCD and the NDE calculated with the SSI, this indicates that more bedrock, and thus less groundwater storage capacity, led to more streamflow droughts. From this it is possible to conclude that in the northern parts of Sweden the drought sensitivity of the catchments was partly driven by the capacity to store groundwater. This relationship would be expected in other parts of the country too, since groundwater is an important factor for drought development (Tallaksen, Hisdal and Van Lanen, 2009; Van Lanen et al., 2013), but there it might have been overshadowed by other land cover characteristics that affect the water storage. A deeper investigation of how the groundwater affects drought development in Swedish catchments was beyond the scope of this study due to time constraints.

Wetlands, the degree of catchment regulation and the surface area of lakes and streams are all land cover characteristics that reflect a capacity to store water. These characteristics would thus be supposed to be negatively correlated to the occurrence of drought events. Van Loon and Van Lanen (2012) found the catchments ability to store water to be a major factor for drought propagation. In this study, the correlations between these characteristics varied depending on how the catchments were grouped. The strongest correlations between the drought characteristics and the percentage of wetlands were in northern Sweden where both the NDE and TCD were negatively correlated to it (Fig. 15). According to Bullock and Acreman (2003) wetlands have the capacity to counteract low flows as well as intensifying them. The results in this study show a tendency for wetlands to reduce the occurrence of drought events, at least in northern Sweden where the majority of the wetlands are located (Fig. 3). In central and southern Sweden the percentage of lakes and streams and how regulated they are, rather than wetland cover, were the characteristics related to water storage that affected the NDE (Fig. 16-17). These results are somewhat in line with the results found by Van Loon and Laaha (2015) in Austrian catchments where the percentage of wetlands and water surfaces were found to be positively correlated to the mean drought duration. In central and southern Sweden there were fewer droughts events (negative correlation for the NDE) in catchments with more regulation or more lakes and streams while the amount of drought days were unchanged (almost no significant correlations for the TCD) thus the drought events that occurred would have lasted longer in these catchments. Catchment characteristics associated with capacity to store water can be related to fewer but longer lasting droughts but the results does not reveal how these properties affect the severity of the droughts. A possibility is that these properties attenuate the droughts while also dragging them out in time but at the same time reduce the number of drought events, this is something that would be interesting to look at in future studies.

The role played by the percentage of agriculture in the catchments in the development of hydrological droughts was not very clear from the results in this study. In northern (Fig. 15) and southern Sweden (Fig. 17) there were almost no significant correlations between agriculture and drought characteristics. For northern Sweden this might be because there is very little farmland located there (Fig. 3). For southern Sweden, where most of the farmland is located (Fig. 3), there is no obvious explanation for the lack of significant correlations. However, in central Sweden agriculture was correlated to fewer drought events but not to the number of drought days (Fig. 16) meaning that the droughts that did occur lasted longer. The same phenomenon was visible when looking at lowland catchments where agriculture was positively correlated to the TCD but with no significant correlations to the NDE (Fig. 14). When looking at all catchments together there was also a pattern towards fewer hydrological droughts that lasted longer (Fig. 12). Van Loon and Laaha (2015) also found the percentage of agriculture in Austrian catchments to be related to longer lasting droughts, which supports the results found in this study in some parts of Sweden. An explanation for the relationship between hydrological droughts and agriculture could be the abstraction of water from reservoirs, groundwater storages, lakes and streams for irrigation. Abstraction of water for irrigation could prolong ongoing drought events and result in drought events being pooled together thus resulting in fewer drought events (explaining the negative correlation to the NDE observed in some parts of Sweden).

Van Loon and Laaha (2015) found the percentage of forests to be positively correlated to both the duration and the magnitude of hydrological drought events in Austrian catchment areas. In this study the percentage of forests in Swedish catchments was negatively correlated with the NDE in both northern and central Sweden. In central Sweden there were no significant correlations with the TCD (Fig. 16), which would mean an increase of the mean duration for the drought events that occurred (fewer drought events but no change in the number of drought days mean the events lasted longer). This was also visible when looking at all catchments grouped together (Fig. 12). However, in northern Sweden there were negative correlations between the percentage of forests and the TCD (Fig. 15), pointing towards both fewer and shorter drought events. So the results in central Sweden or when looking at all catchment grouped together were in line with the results found by Van Loon and Laaha (2015). The results in northern Sweden with fewer and shorter hydrological droughts in catchment areas with more forest is supported by the arguments put forward by Ellison, Futter and Bishop (2012) that the increased evapotranspiration created by forests lead to more precipitation on a regional scale, which theoretically would result in fewer droughts.

Mean precipitation over the whole 30-year period showed mostly positive correlations with the drought characteristics calculated with the SSI and threshold index no matter how the catchments were grouped. These correlations are very counter-intuitive since it would be natural to assume that more precipitation would lead to fewer hydrological droughts. The reason for this could be the same as mentioned in 4.3.1. when looking at the correlations between the SPI and the mean precipitation. Very wet events could lead to skewed probability distributions resulting in more days with streamflow below "normal" conditions.

In all three parts of Sweden, but especially in the north (Fig. 15), and in the mountainous catchments (Fig. 13) there were positive correlations between the drought characteristics and the mean elevation. This indicates that the drought sensitivity increases with elevation in all parts of Sweden. The same correlation between streamflow drought duration and mean elevation was found by Van Loon and Laaha (2015) in Austria. At higher altitudes in the mountains stronger flow seasonality is expected with high flows concentrated in short seasons (Van Loon and Laaha, 2015). Also, higher elevations would be expected to lead to longer winters (Swedish Meteorological and Hydrological Institute, 2009) and more persistent snow cover and thus longer winter droughts followed by large spring flood peaks. However, the fact that there were no significant correlations between the TCD and mean elevation in the mountainous catchments means that the number of drought days does not increase with altitude in the mountains. This does not necessarily indicate that there is no increase in the length of winter droughts at higher altitudes since it could be a result of not separating winter and summer droughts. It is possible that there is a shift from summer to winter droughts in the mountainous catchments with increasing elevation that is not detectable without studying winter and summer droughts separately. When looking only at lowland catchments grouped together there were negative correlations between mean elevation and some SSI AP. This is probably because by removing all mountainous catchments the differences in elevation became much less important and other parameters became more influencing. In the north of Sweden, the percentage of bedrock was correlated to the mean elevation ($\tau = 0.68$). Therefore, it is possible that the positive correlation between hydrological droughts and mean elevation in northern Sweden was in fact driven by the percentage of bedrock. There was also a positive relationship between the mean elevation and the mean precipitation during the whole period in northern Sweden ($\tau = 0.58$) and in central Sweden ($\tau = 0.49$). This opens the possibility that one of the underlying explanations why the hydrological drought sensitivity increased with elevation in these two parts of the country was because of the increased precipitation in higher altitudes. The reasons why a higher precipitation might cause the SPI and the SSI to show more droughts have already been explained, very wet events could lead to skewed probability distributions resulting in more daily streamflow values falling below the “normal” streamflow values.

4.4. CORRELATION BETWEEN THE DROUGHT CHARACTERISTICS FOR THE DIFFERENT INDICES

4.4.1. Number of drought events (NDE)

The NDE for the different SSI AP correlated positively with each other. Meaning that the estimated NDE follow a similar pattern everywhere in Sweden no matter which AP was used for the SSI. That the TH-NDE correlated best with the SSI_1-NDE is not surprising since both are based on a one-month window/AP. For the SPI the correlations between the NDE for the different AP were not as many or as strong as for the SSI. There were even negative correlations between the SPI_1-NDE and the SPI_2-NDE in the north of Sweden. Therefore the result when studying the NDE over a period will depend on which AP is chosen to a higher degree for the SPI than for the SSI. The correlations for the NDE between the different SPI AP and the SSI AP varied depending on how the catchments were grouped. There were both negative and positive correlations between them. This shows that using an index based on precipitation or on streamflow will influence the estimations of the NDE.

4.4.2. Total number of cumulative drought days (TCD)

For the TCD there were fewer significant correlations between the indices than for the NDE. The strongest positive correlations were for neighboring AP for the same index, especially for the SSI, e.g. SSI_2-TCD correlated strongest with SSI_1-TCD and SSI_3-TCD. The TCD results appear to depend more on which AP is chosen than the NDE, at least for the SSI. For the SPI the TCD does not appear to be as dependent on the AP as the SSI since the different SPI AP showed more correlations with each other, not only with the neighboring AP. Over all it appears the most number of positive correlations between the SPI and the SSI were between the long-term SPI AP and the SSI. This could mean that the long-term SPI AP are better suited to predict the amount of streamflow drought days from precipitation data than short-term SPI AP. This is in line with the results from the lag period analysis where the correlations between the SSI and the SPI were stronger for longer AP and also with the fact that SPI calculated with a 12-months AP or longer is more related to changes in streamflow or reservoir and groundwater levels than SPI calculated with shorter AP (Khan, Gabriel and Rana, 2008; World Meteorological Organization, 2012).

4.5. METHODOLOGICAL UNCERTAINTIES

Using longer time series for precipitation and streamflow would have improved the parameter estimations when fitting the probability distributions. It would also have given a longer period over which to estimate the probability of a drought event more accurately. By using a shorter time period there was less information about long-term drought patterns and how a changing clime affects the drought development. The reason behind the choice to only use a 31-year time period was that it was the longest period with overlapping records from all stations, in order to compute and evaluate the indices over the same time period for all stations. An option would have been to estimate the distribution parameters for the SPI and SSI for the whole available data series, which were longer for some stations, and then evaluate them for a shorter overlapping period. This would have resulted in better parameter estimations for some of the individual data series but at the same time comparison between the results for the different stations would have been less justified if the data series spanned over different years. The risk of using different time series for the parameter estimations is that it could introduce a period of very wet or dry years for one station which then affect the index, since the SPI and SSI are based on the probability of an event occurring, and make it differ from another station were those years were not recorded. In short it would improve the parameter estimations for some data series but it would make it difficult to compare the results between the stations. So, the choice was between using a longer time period but fewer stations or a shorter time period and more stations. The choice fell on a shorter time period but including as many catchments as possible to get an extensive spatial coverage of Sweden. Nevertheless, using a 31-year period is in accordance with the minimum recommendations in earlier studies, McKee et al. (1993) recommend using a continuous time period of at least 30 years for the SPI, others (e.g. Stagge et al., 2015) also used a 30-year reference period.

For the threshold index there were subjective choices when choosing which percentile to use as the threshold level and how to classify minor droughts to pool or remove. The choices made in this study were within the recommended ranges in the literature (e.g. Hisdal et al., 2004). But a different threshold level or removing more or less minor droughts would change the results. However, due to time constraints, no sensitivity analysis was done to investigate how much these choices affected the results. But some of the differences between the SSI and the threshold index might be a result of this.

The fact that the study does not separate winter droughts from summer droughts might be a concern when investigating the relationship between droughts and catchment characteristics for the SSI and the threshold index. If winter droughts due to snow accumulation are driven by other factors than summer droughts it would be necessary to divide the year into a winter period, with temperatures below 0˚C, and a summer period and investigate the driving factors separately. However, the length of the winter and summer periods will differ depending on where in the country the catchment is located and therefore it would not be easy to compare catchments in different parts of the country. This together with the fact that the main study focus was on studying spatial relations were the principal reasons why this approach was not used in this.

5. CONCLUDING REMARKS

- Two major drought events covering the whole country were identified with the SPI and the SSI. The drought events, occurring in the hydrological years of 1995-1996 and 2002-2003, were confirmed with old reports.
- Which meteorological driving variables and catchment properties that promoted drought development varied depending on how the catchments were grouped according to latitude or mean elevation, which index was used and also to some degree on the AP. The driving variables affected the occurrence of droughts to different degrees and in various ways in different parts of the country. It was not possible to identify a general driving variable for drought events in all Swedish catchments.
- The SPI and the SSI correlated best over time when the SSI was shifted with a one month delay, indicating that there is a time lag lasting about a month (between no lag and two months) between meteorological and hydrological droughts in Swedish catchments. The correlations between the SPI and the SSI were more positive with longer AP, for the longest AP (12 months) the mean τ was 0.64.
- There were no significant trends ($p < 0.05$) for the NDE or the TCD in a majority of the 235 catchments during 1983-2013. However, there was an area in the central parts of southern Sweden where significant negative trends for the NDE and the TCD were observed for several streamflow gauging stations, for all indices used in the study. There were also areas in Skåne, Jämtland and Ångermanland where positive trends were observed for the NDE and the TCD for several streamflow gauging stations calculated with the hydrological indices, the SSI and the threshold index, during the study period.
- When estimating the NDE, the SPI was more sensitive to which AP was used than the SSI. However, when estimating the TCD, the SPI did not appear to as dependent on which AP was used as the SSI was. Correlations between the SPI

and the SSI for the NDE varied depending on how the catchments were grouped while for the TCD there were a pattern with positive correlations between long term SPI AP and the SSI.

For future studies about which meteorological variables or catchments characteristics that promote hydrological droughts in Swedish catchments it would be recommended to look separately at winter and summer droughts. A possible approach to winter and summer droughts would be to divide the catchments into groups according to latitude where the catchments can be said to have the same length of winter and summer periods and only make comparisons between the catchments within these groups.

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APPENDIX A

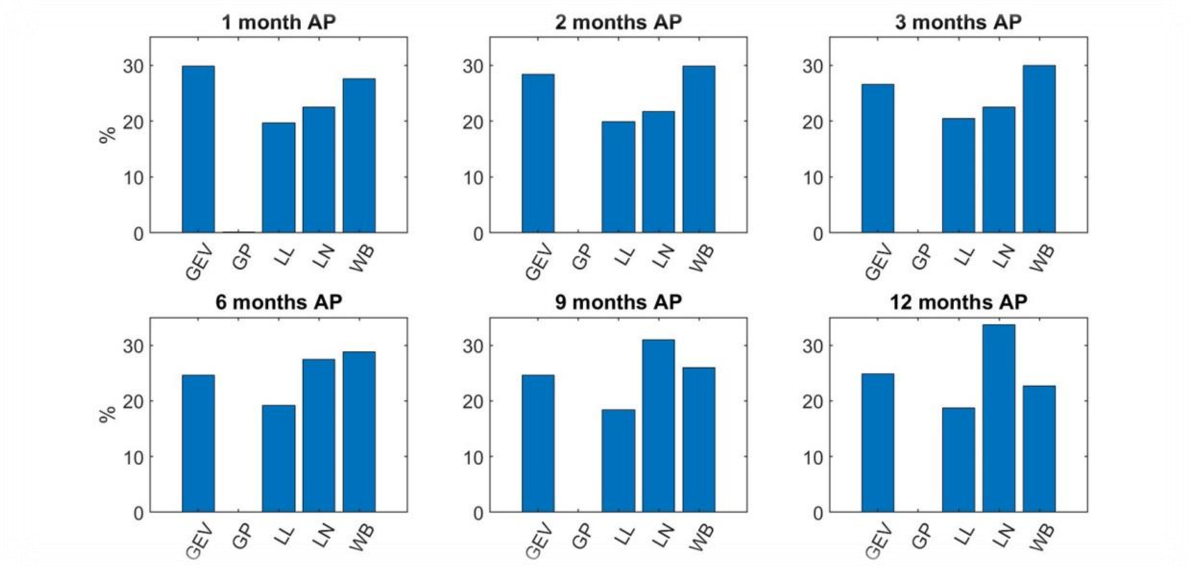

Figure A1 The frequency that different probability distribution gave the best fit to the streamflow data for each AP. The distributions were fitted to the series of accumulated daily streamflow for the same day over all 30 years for all 235 stations. This was done for all different AP, 1 month = 31 days, 2 months = 61 days, 3 months = 91 days, 6 months = 183 days, 9 months = 247 days and 12 months = 365 days. The fitted distributions were the GEV = generalized extreme value distribution, GP = generalized Pareto distribution, LL = loglogistic distribution, LN = lognormal distribution and WB = Weibull distribution.

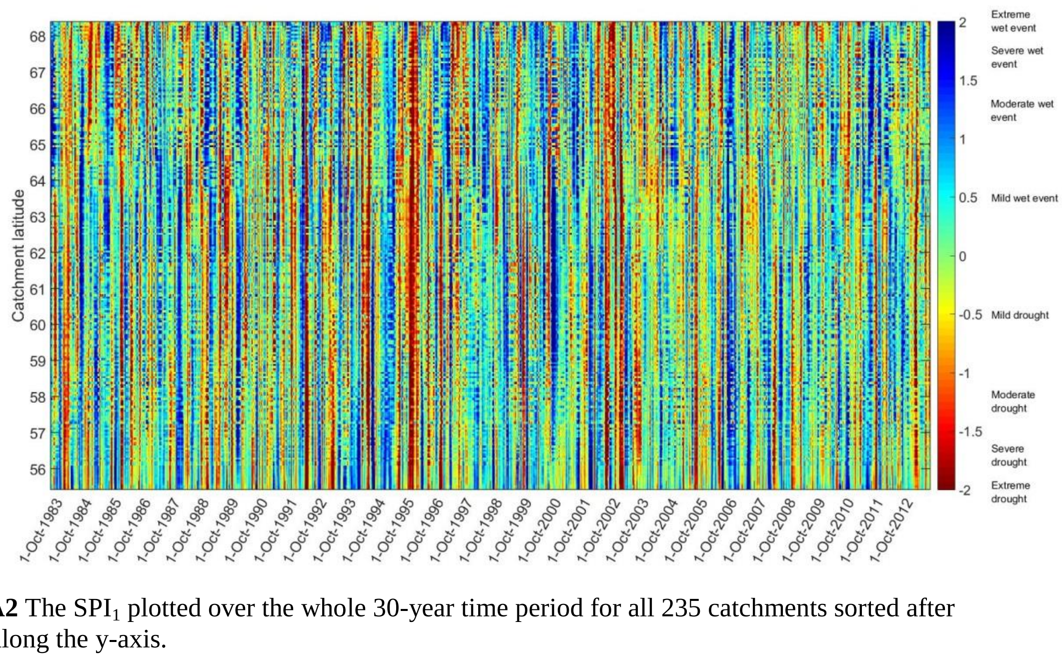

Figure A2 The SPI_1 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

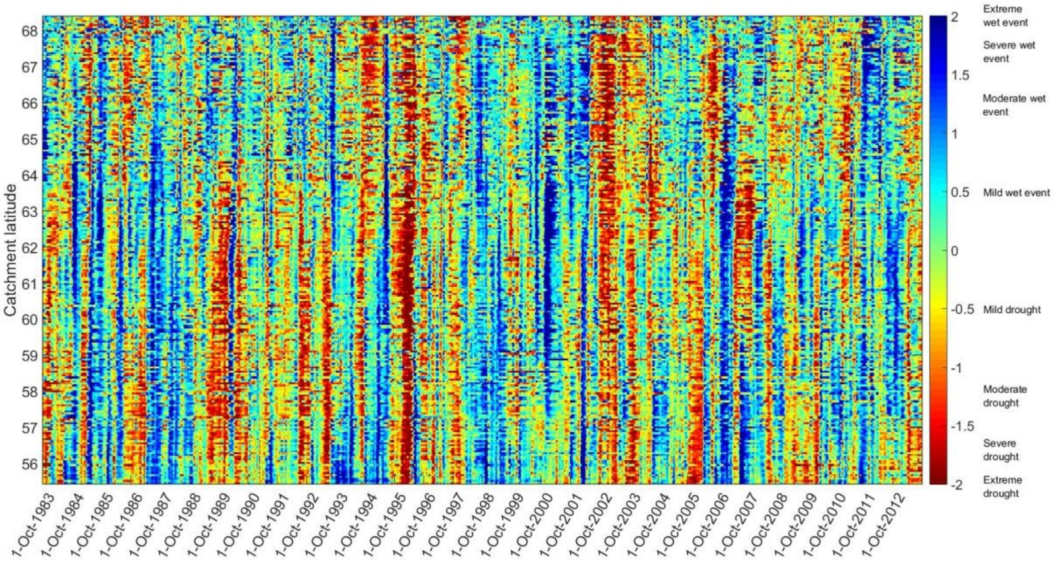

Figure A3 The SSI_1 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

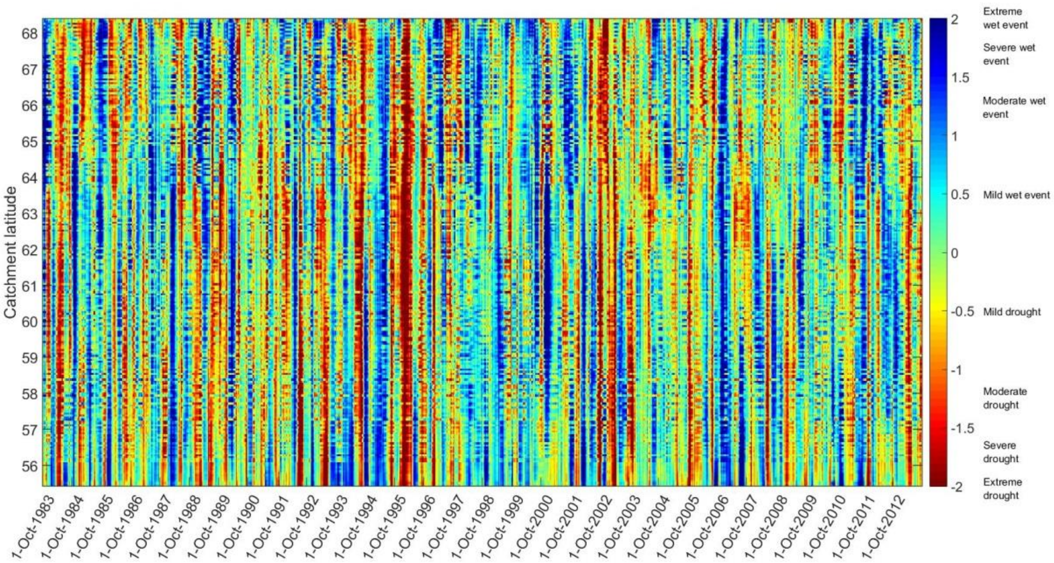

Figure A4 The SPI_2 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

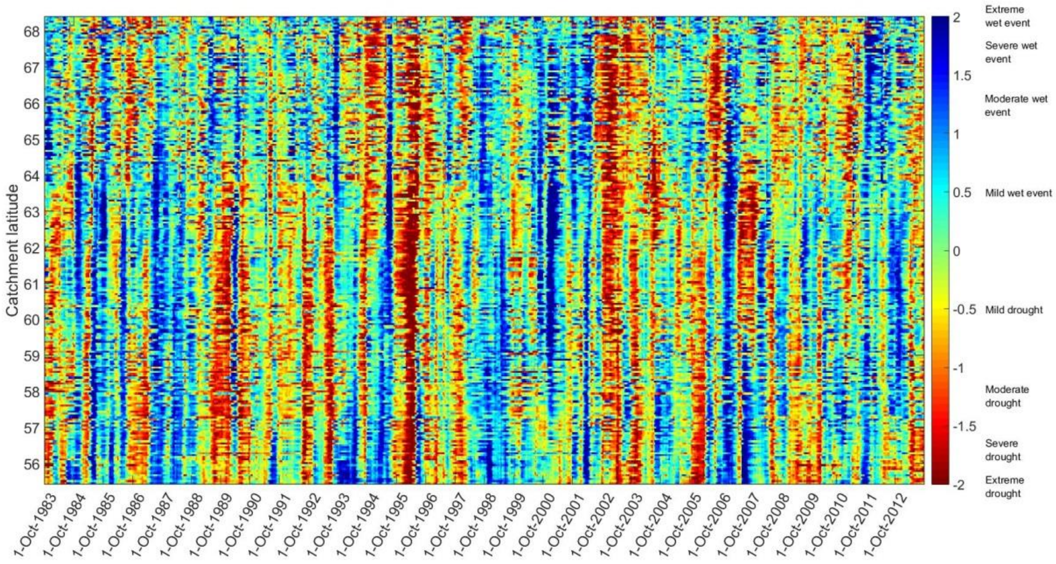

Figure A5 The SSI_2 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

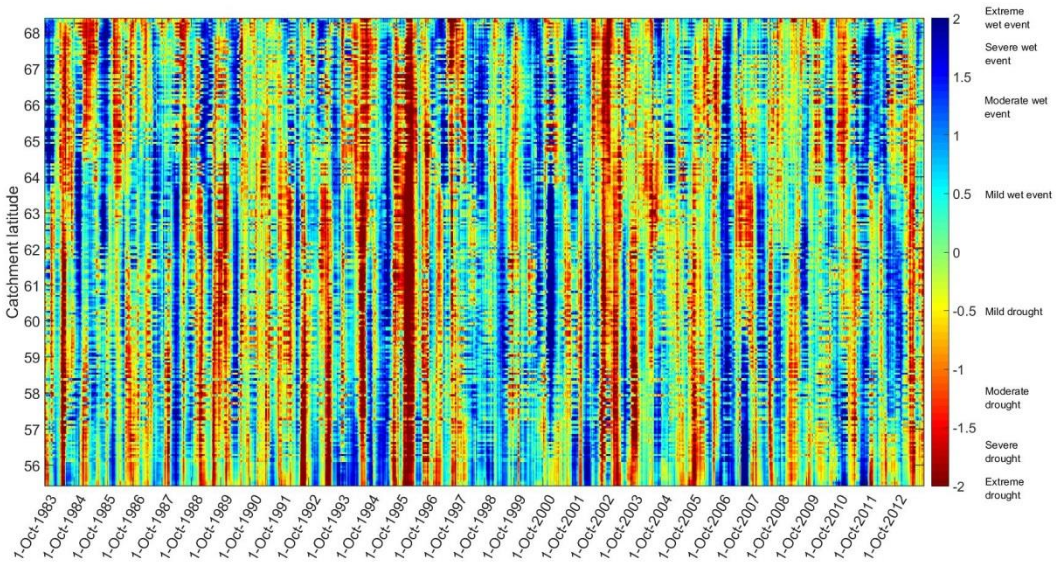

Figure A6 The SPI_3 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

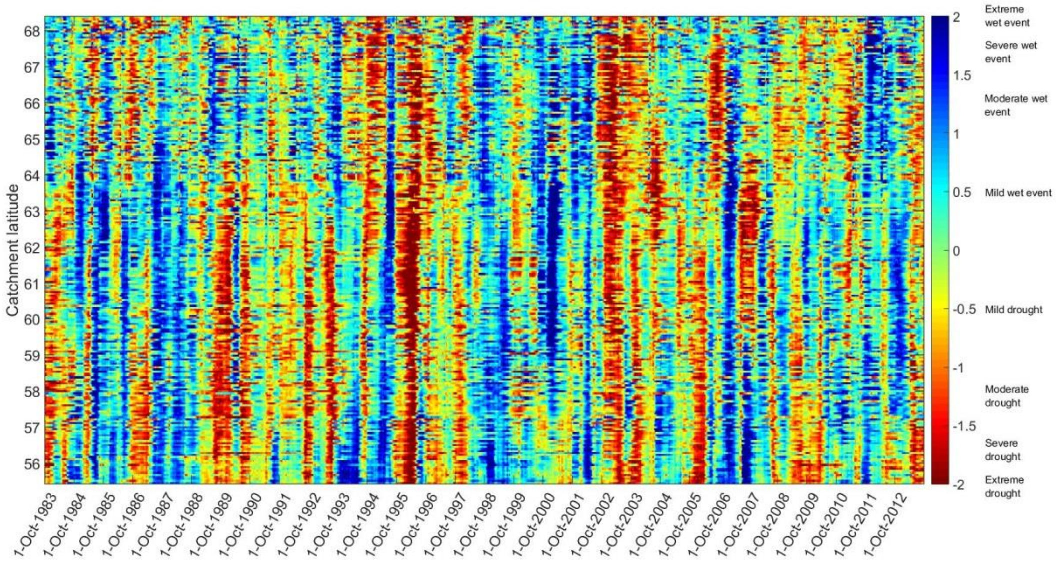

Figure A7 The SSI_3 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

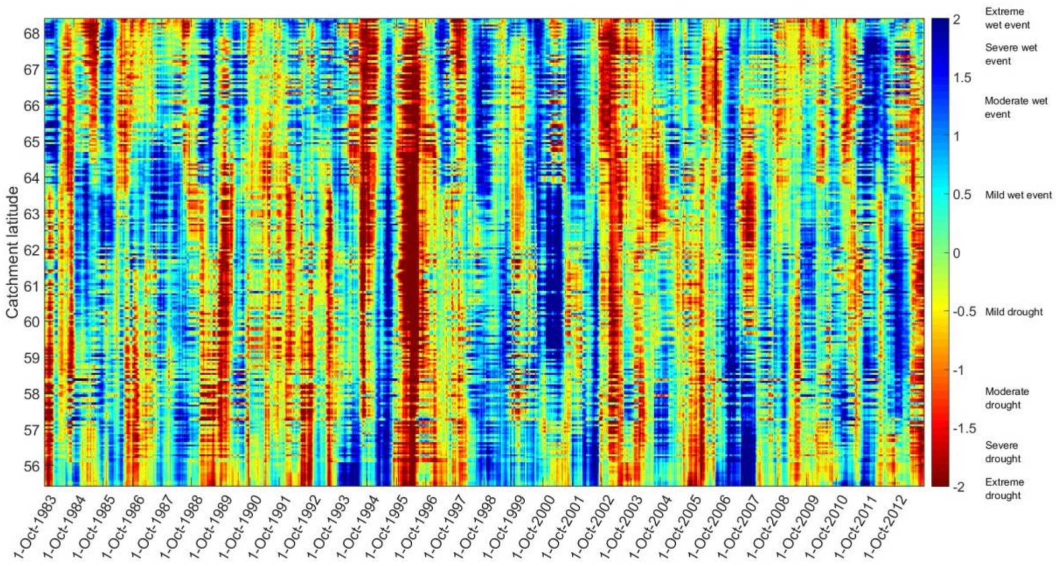

Figure A8 The SPI_6 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

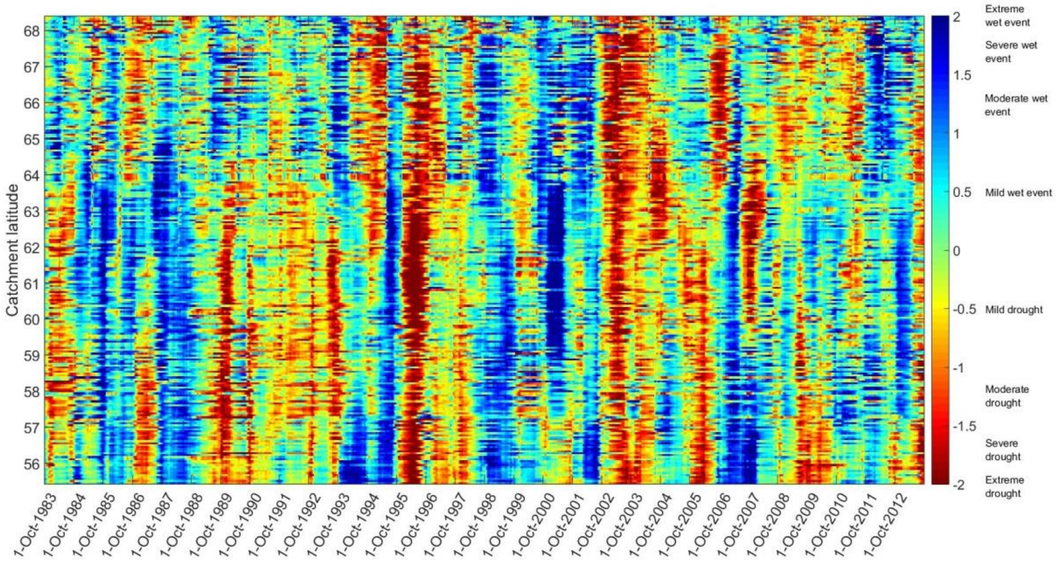

Figure A9 The SSI_6 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

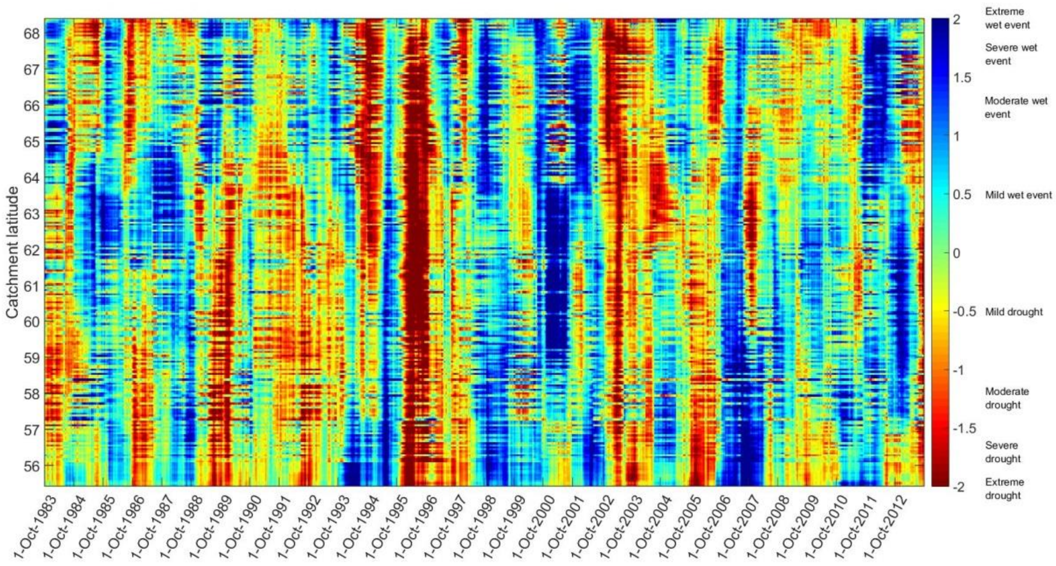

Figure A10 The SPI_9 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

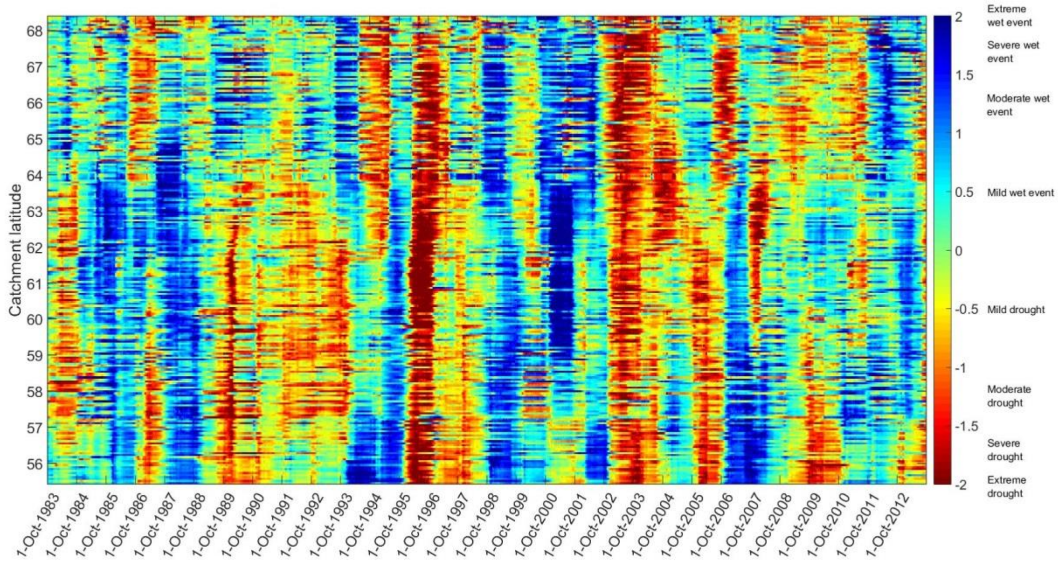

Figure A11 The SSI_9 plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

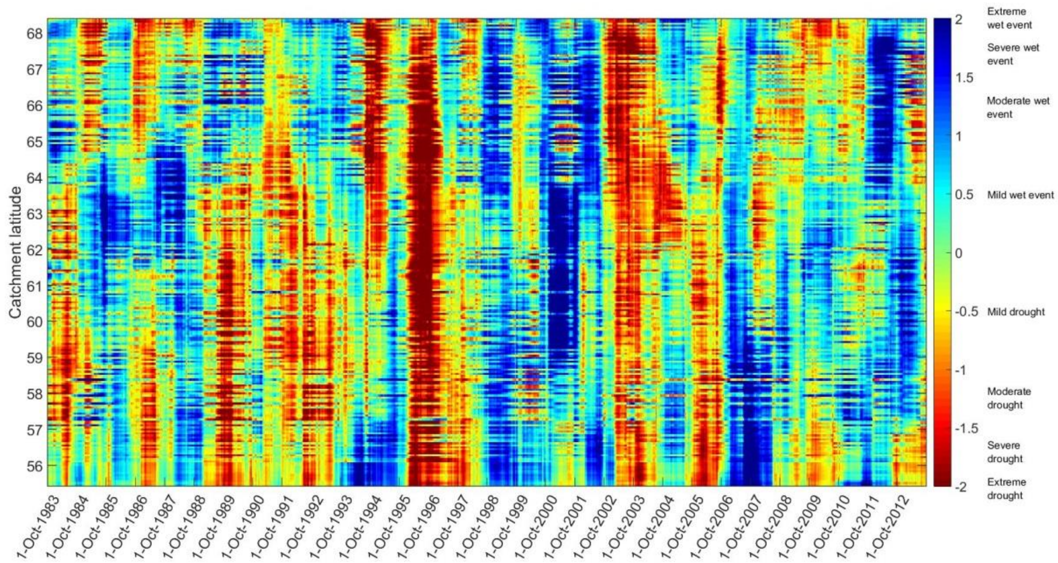

Figure A12 The SPI_{12} plotted over the whole 30-year time period for all 235 catchments sorted after latitude along the y-axis.

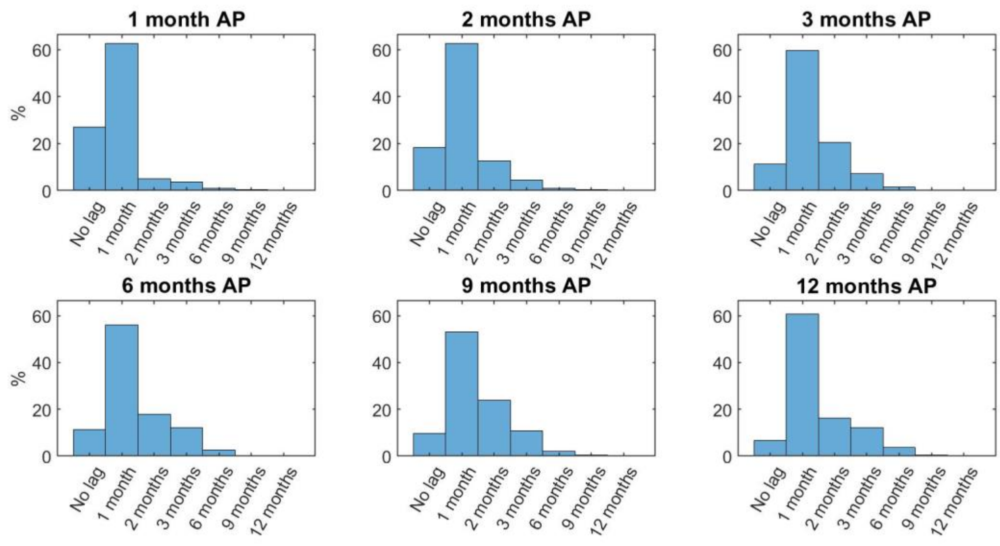

Figure A13 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for the 196 lowland catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

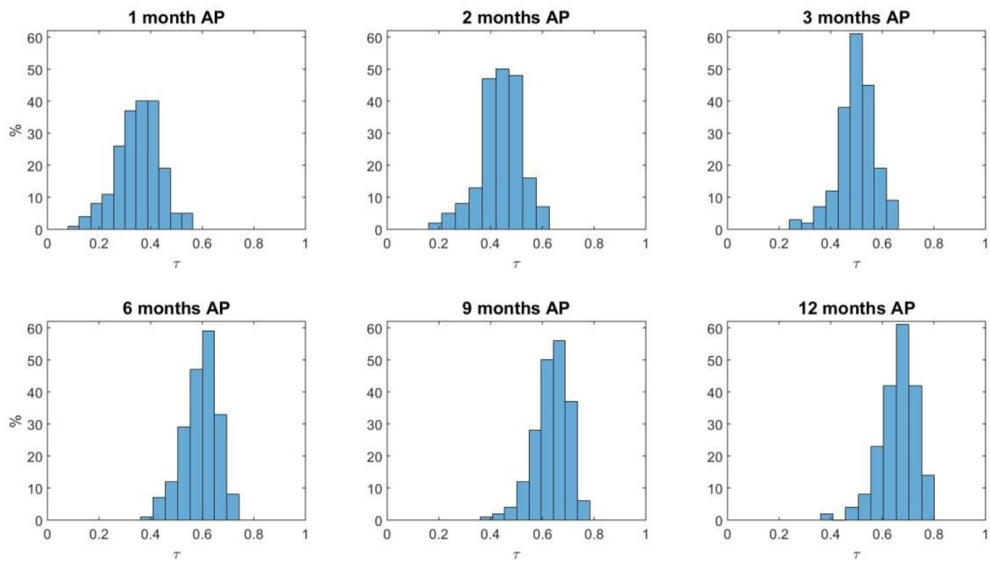

Figure A14 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for the 196 lowland catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

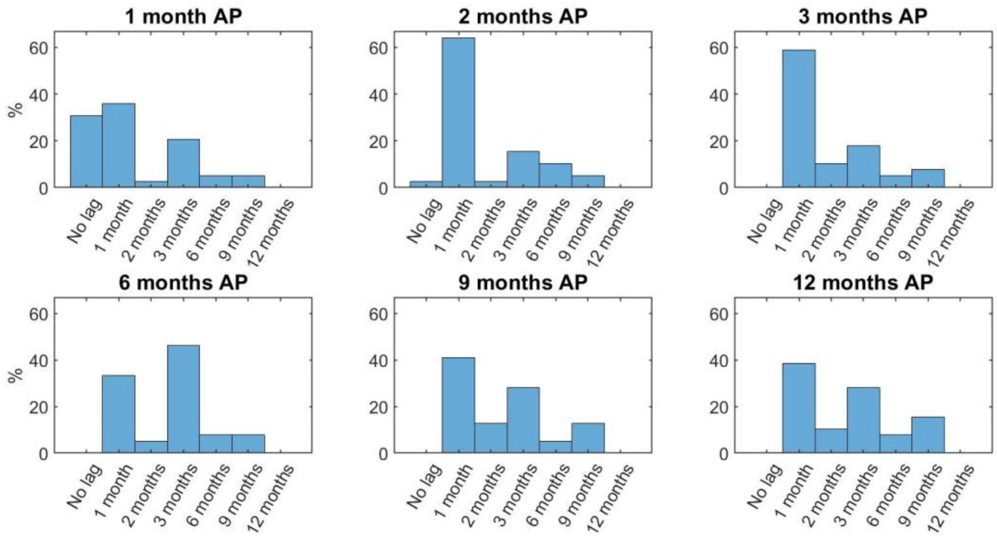

Figure A15 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for the 39 mountainous catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

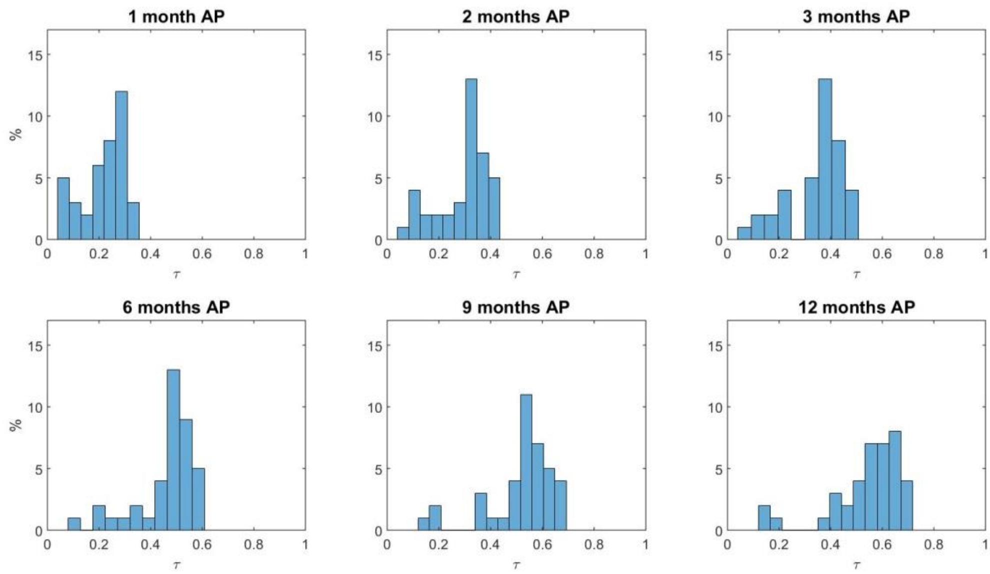

Figure A16 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for the 39 mountainous catchments for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

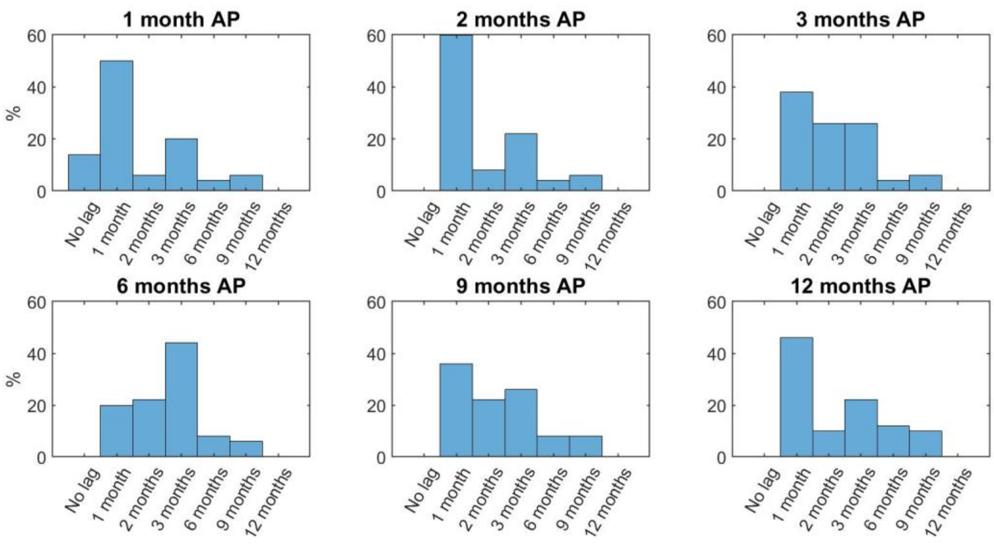

Figure A17 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for the 50 catchments in northern Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

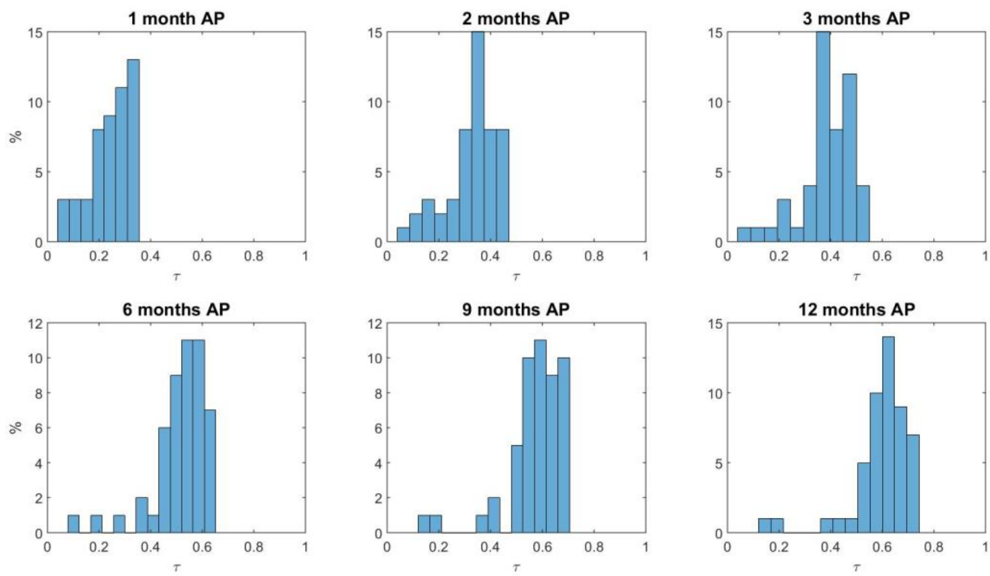

Figure A18 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for the 50 catchments in northern Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

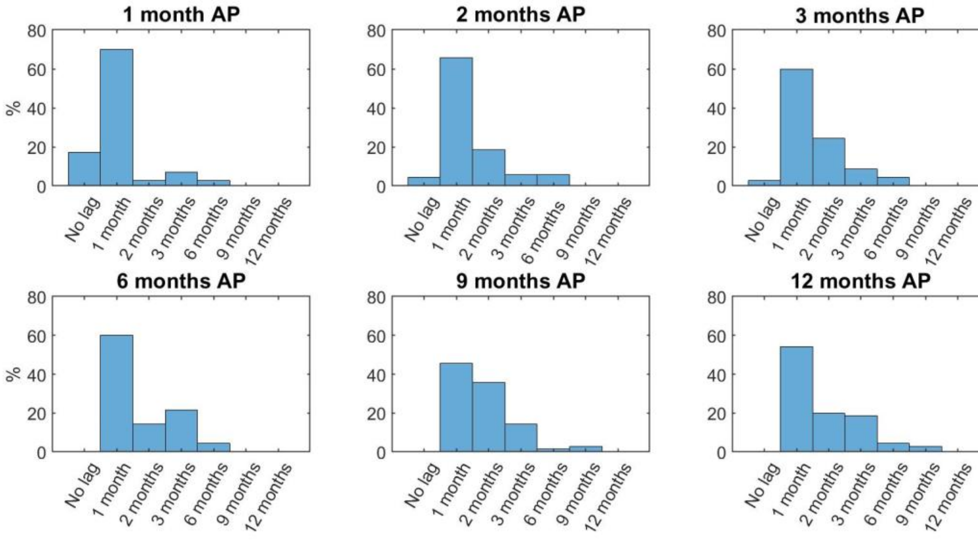

Figure A19 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for the 70 catchments in central Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

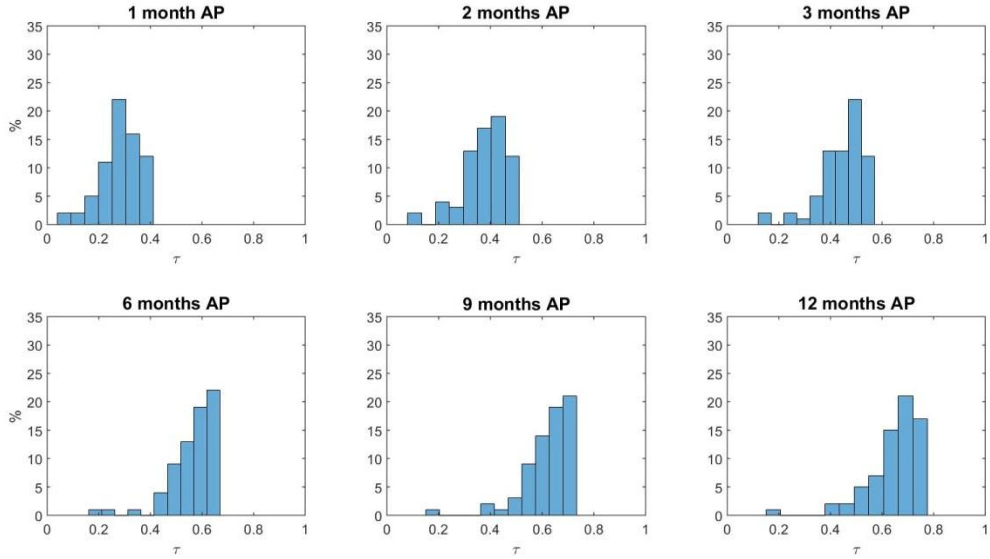

Figure A20 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for the 70 catchments in central Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

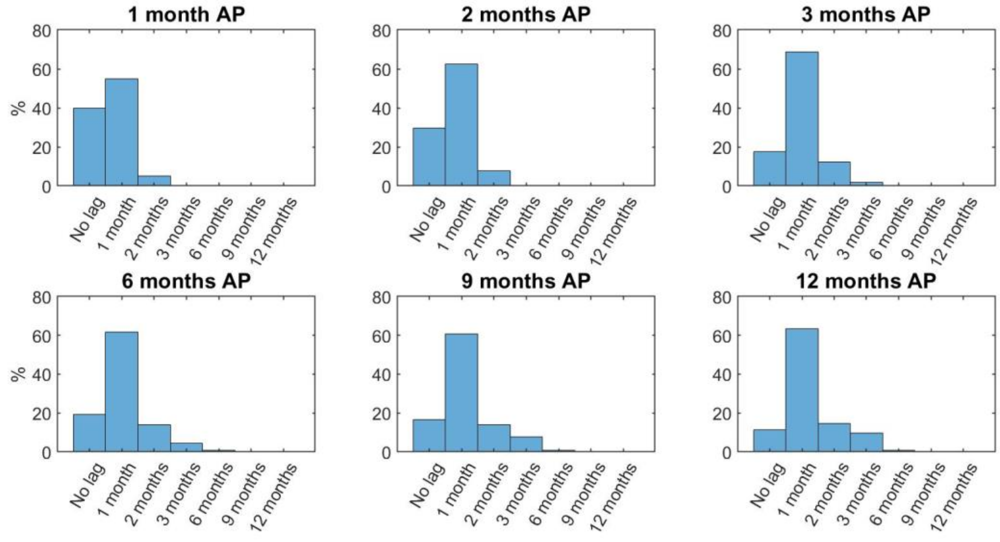

Figure A21 The percentage of times that the different lag periods gave the strongest positive correlation between the SPI and the SSI for the 115 catchments in southern Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

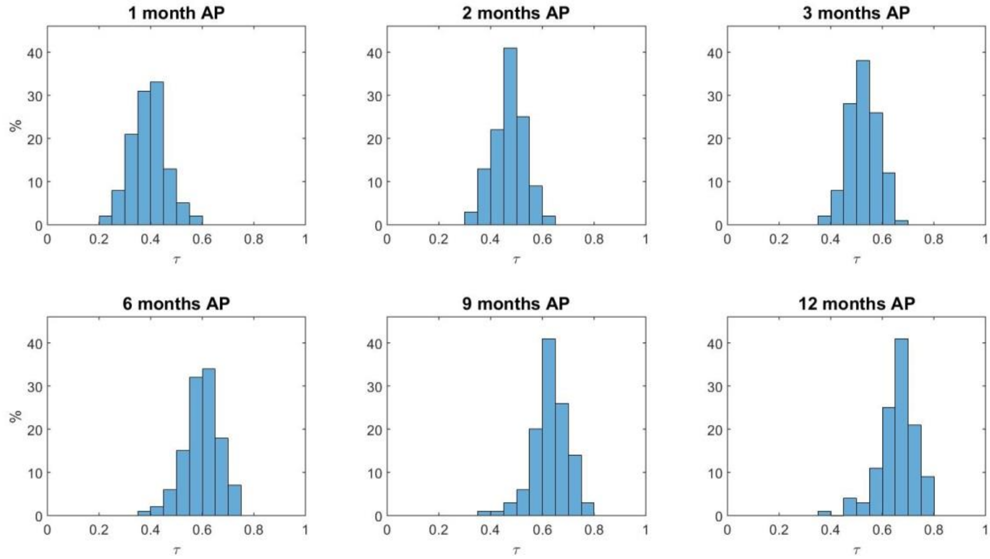

Figure A22 Histogram showing the obtained τ from the strongest positive correlation between the SPI and the SSI for the 115 catchments in southern Sweden for the different AP. The correlations were done with Kendall's Tau using a significance level $p < 0.05$.

APPENDIX B

Code to calculate the SSI:

```
% Calculate the SSI
% Choose which accumulation period to use
A = 25; % Row with data with chosen acc. period
B = 10; % Row in SSI for output

for h = 1:length(data)
    for j = 1:365
        clear k ID id

        k = [1:5]; % k(1)=k_GEV, k(2)=k_LL, k(3)=k_LN, k(4)=k_WB, k(5)=k_GP

        % Find eventual zero values in the data, if there are zeros:
        % separate the data into nonzero values and zeros. The probability
        % distributions are fitted to nonzero data while the probability of
        % zeros is calculated separately.
        ZEROS = [];
        ZEROS = find(~data{A,h}(:,j));
        Z = isempty(ZEROS);
        if Z == 1 % ZEROS is empty, there are no zeros in the data
            data = data{A,h}(:,j);
            prob_zero = 0;
        elseif Z == 0 % ZEROS is not empty, there are zeros in the data
            rows = find(data{A,h}(:,j)); % Find rows with nonzero values
            data = data{A,h}(rows,j);
            zeros = data{A,h}(ZEROS,j);
            prob_zero = length(zeros)/(length(data{A,h}(:,j))+1);
        end

        % Fit six different probability distribution to the streamflow data
not containing zeros.
        % check which dist. can handle zeros
        GEV = fitdist(data,'gev'); % Generalized extreme value
        LL = fitdist(data,'loglogistic'); % Log-logistic
        LN = fitdist(data,'lognormal'); % Lognormal
        WB = fitdist(data,'wbl'); % Weibull
        GP = fitdist(data,'gp'); % Generalized Pareto

        y = (1:length(data{A,h}(:,j)))/(length(data{A,h}(:,j))+1); % Get the
probability values for all data points
        datasorted = sort(data{A,h}(:,j));

        % Calculate the vertical difference between the empirical
        % distribution and the cumulative distribution function for the six
        % fitted distributions.

        % For Generalized extreme value
        icdf_GEV = icdf('gev',y,GEV.k,GEV.sigma,GEV.mu);
        [h_GEV,p_GEV,k_GEV] = kstest2(datasorted,icdf_GEV);
        % For Log-logistic
```

```
        icdf_LL = icdf(LL,y); % Gives the same result as calling the icdf in
the way used for the other dist.
```

```
        [h_LL,p_LL,k_LL] = kstest2(datasorted,icdf_LL);
        % For Lognormal
        icdf_LN = icdf('logn',y,LN.mu,LN.sigma);
        [h_LN,p_LN,k_LN] = kstest2(datasorted,icdf_LN);
        % For Weibull
        icdf_WB = icdf('wbl',y,WB.A,WB.B);
        [h_WB,p_WB,k_WB] = kstest2(datasorted,icdf_WB);
        % For Generalized Pareto
        icdf_GP = icdf('gp',y,GP.theta);
        [h_GP,p_GP,k_GP] = kstest2(datasorted,icdf_GP);

        k(1)=k_GEV;
        k(2)=k_LL;
        k(3)=k_LN;
        k(4)=k_WB;
        k(5)=k_GP;
        Min = min(k); % Chose dist. that gives the smallest D.

        % Check if there are several distributions that result in the same
        % smallest k.
        nk = 0;
        GH = 0;
        ID = [];
        id = [];
        for HH = 1:length(k)
           if k(HH) == Min
                nk = nk+1; % Count how many k's are equal to the smallest
value.
                ID(nk) = HH; % Save the position in k to keep track of which
dist. need to be compared with MSE.
            elseif k(HH) > Min
                GH = GH+1;
                id(GH) = HH; % Save position of k > min(k).
            end
        end
        % if there are several dist. that gives the same smallest k then
        % use MSE to determine best fit between them.
        ds = datasorted';
        if nk >= 2
            for IJ = 1:length(ID)
                if ID(IJ) == 1
                    k(1) = immse(ds,icdf_GEV); % MSE_GEV
                elseif ID(IJ) == 2
                    k(2) = immse(ds,icdf_LL); % MSE_LL
                elseif ID(IJ) == 3
                    k(3) = immse(ds,icdf_LN); % MSE_LN
                elseif ID(IJ) == 4
                    k(4) = immse(ds,icdf_WB); % MSE_WB
                elseif ID(IJ) == 5
                    k(5) = immse(ds,icdf_GP); % MSE_ GP
                end
            end
```

```
            % Then update the k for the distributions where no MSE was
            % calculated and make sure that they are bigger than the
            % calculated MSE in case their result from the kstest2 are
            % smaller than the MSEs.
            Max = max(k);
            for IH = 1:length(id)
                if id(IH) == 1
                    k(1) = Max+1;
                elseif id(IH) == 2
                    k(2) = Max+1;
                elseif id(IH) == 3
                    k(3) = Max+1;
                elseif id(IH) == 4
                    k(4) = Max+1;
                elseif id(IH) == 5
                    k(5) = Max+1;
                end
            end
            Min = min(k); % Find smallest MSE.
        end

        % prob_zero = number of zeros / n+1
        prob_GEV = prob_zero+(1-
prob_zero).*cdf('gev',data{A,h}(:,j),GEV.k,GEV.sigma,GEV.mu);
        prob_LL = prob_zero+(1-prob_zero).*cdf(LL,data{A,h}(:,j)); % Gives the
same result as calling the cdf in the way used for the other dist.
        prob_LN = prob_zero+(1-
prob_zero).*cdf('logn',data{A,h}(:,j),LN.mu,LN.sigma);
        prob_WB = prob_zero+(1-
prob_zero).*cdf('wbl',data{A,h}(:,j),WB.A,WB.B);
        prob_GP = prob_zero+(1-
prob_zero).*cdf('gp',data{A,h}(:,j),GP.k,GP.sigma,GP.theta);

        % Depending on which distribution resulted in the smallest k value,
        % the corresponding cumulative probability distribution is used to
        % compute the SSI index.

        if Min == k(4) % Choose Weibull dist.
            SSI{B,h}(:,j) = norminv(prob_WB,0,1);
            nWB = nWB+1;
        end
        if Min == k(5) % Choose Generalized Pareto.
            SSI{B,h}(:,j) = norminv(prob_GP,0,1);
            nGP = nGP+1;
        end
        if Min == k(1) % Choose Generalized extreme value dist.
            SSI{B,h}(:,j) = norminv(prob_GEV,0,1);
            nGEV = nGEV+1;
        end
        if Min == k(2) % Choose Log-logistic dist.
            SSI{B,h}(:,j) = norminv(prob_LL,0,1);
            nLL = nLL+1;
        end
        if Min == k(3) % Choose Lognormal dist.
```

```
            SSI{B,h}(:,j) = norminv(prob_LN,0,1);
            nLN = nLN+1;
        end
    end
end
```

Code to calculate the SPI:

```
% calculate SPI
% Choose which accumulation period to use
A = 35; % Row with data for 1 month accumulation period
B = 13; % Row in SPI for SPI-1

for h = 1:length(data)
    for j = 1:365

        % Find eventual zero values in the data, if there are zeros:
        % separate the data into nonzero values and zeros. The gamma
probability
        % distribution is fitted to nonzero data while the probability of
        % zeros is calculated separately.
        ZEROS = [];
        ZEROS = find(~data{A,h}(:,j));
        Z = isempty(ZEROS);
        if Z == 1 % ZEROS is empty, there are no zeros in the data
            data = data{A,h}(:,j);
            prob_zero = 0;
        elseif Z == 0 % ZEROS is not empty, there are zeros in the data
            rows = find(data{A,h}(:,j)); % Find rows with nonzero values
            data = data{A,h}(rows,j);
            zeros = data{A,h}(ZEROS,j);
            prob_zero = length(zeros)/(length(data{A,h}(:,j))+1);
        end

        % Fit the gamma probability distribution to the accumulated
        % precipitation data
        Gamma_pd = fitdist(data,'gamma');
        Gamma_prob = prob_zero+(1-
prob_zero).*gamcdf(data{A,h}(:,j),Gamma_pd.a,Gamma_pd.b);
        SPI{B,h}(:,j) = norminv(Gamma_prob,0,1);

    end
end
```

Code to calculate the threshold index:

```
% Calculate the daily deviation from a variable threshold. The thresholds are
% calculated for each day over the year using a daily window for all years.
% Ex. the threshold for July 15 is calculated by taking the 80th percentile
% for all streamflow values from July 1 to July 30 for all the years in the
```

```
% time series (1983-2013).

clear I;

for h = 1:length(data_P_T_Q_235)
    k=1;
    TH = [];
    for year = 1983:2012
        I(k) = find(data_P_T_Q_235{8,h}(:,1) == year &
data_P_T_Q_235{8,h}(:,2) == 10 & data_P_T_Q_235{8,h}(:,3) == 1); % Find the
starting cells for all hydrological years
        k = k+1;
    end
    for j = 1:365
      for i = 1:length(I)
            AP(:,i) = data_P_T_Q_235{8,h}((I(i)-14+j-1):(I(i)+15+j-1),4); %
Use a 30 day window
      end
      window = reshape(AP,[],1);
      TH(j) = quantile(window,.20); % 80th percentile is set as threshold for
day j of the year
      threshold{8,h}(:,j) = data_P_T_Q_235{21,h}(2:31,j)-TH(j); % Calculate
the daily deviation from the threshold
    end
end
```