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Regional Quantification of Climatic and Anthropogenic Impacts on Streamflows in Sweden

Regional kvantifiering av påverkan från klimat och mänsklig aktivitet på vattenflöden

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Sofia Hedberg

ABSTRACT

Regional Quantification of Climatic and Anthropogenic Impacts on Streamflows in Sweden
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The anthropogenic impact on earth's systems has rapidly increased since the middle of the last century and today it is hard to find a stream that is not influenced by human activities. The understanding of causes to changes is an important knowledge for future water management and planning and of that reason climatic and anthropogenic impact on streamflow changes in Sweden were explored and quantified. In the first step trends and abrupt changes in annual streamflow were detected and verified with the non-parametric Mann-Kendall's and Pettitt's test, all performed as moving window tests. In the second step HBV, a climatic driven rainfall-runoff model, was used to attribute the causes of the detected changes. Detection and attribution of changes were performed on several catchments in order to investigate regional patterns. On one hand using smaller window sizes, period higher number of detected positive and negative trends were found. On the other hand bigger window sizes resulted in positive trends in more than half of the catchments and almost no negative trends. The detected changes were highly dependent on the investigated time frame, due to periodicity, e.g. natural variability in streamflow. In general the anthropogenic impact on streamflow changes was smaller than changes due to temperature and streamflow. In median anthropogenic impact could explain 7% of the total change. No regional differences were found which indicated that anthropogenic impact varies more between individual catchments than following a regional pattern.

Keywords: Rainfall-runoff modeling, Change point and trend detection, time-series analysis, attribution of changes, climatic and anthropogenic impact, HBV-model.

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REFERAT

Regional kvantifiering av påverkan från klimat och mänsklig aktivitet på vattenflöden i Sverige
Sofia Hedberg

Sedan mitten av förra århundradet har den antropogena påverkan på jordens system ökat kraftigt. Idag är det svårt att hitta ett vattendrag som inte är påverkat av mänsklig aktivitet. Att förstå orsakerna bakom förändringarna är en viktig kunskap för framtida vattenplanering och av denna anledning undersöktes och kvantiferades den antropogen och klimatpåverkan på flödesförändringar i svenska vattendrag. I arbetets första steg användes de Mann-Kendalls och Pettitts test för att lokalisera och verifiera förändringar i årligt vattenflöde. Alla test var icke parametriska och utfördes som ett glidande fönster. I nästa steg undersöktes orsakerna till förändringar med hjälp av HBV, en klimatdriven avrinningsmodell. Ett större antal avrinningsområden undersöktes för att upptäcka regionala mönster och skillnader. Perioder med omväxlande positiva och negativa trender upptäcktes med mindre fönsterstorlekar, medan större fönster hittade positiva trender i mer än hälften av områdena och knappt några negativa trender hittades. De detekterade förändringarna var på grund av periodicitet i årligt vattenflöde till stor grad beroende på det undersöka tidsintervallet. Generellt var den antropogena påverkan större påverkan från nederbörd och temperatur, med ett medianvärde där 7 % av den totala förändringen kunde förklaras med antropogen påverkan. Inga regionala skillnader i antropogen påverkan kunde identifieras vilket indikerar att den varierar mer mellan individuella områden än följer ett regionalt mönster.

Nyckelord: Hydrologisk modellering, detektion av trender och abrupta förändringar, tidsserieanalys, orsakskoppling till förändringar, klimat och antropogen påverkan, HBV modellen.

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PREFACE

This master thesis of 30 credits is the final part of the Master of Science program in Water and Environmental engineering at Uppsala University and the Swedish University of Agricultural Science. The project was initiated and supervised by Claudia Teutschbein, post-doctoral researcher. Subject reviewer was Thomas Grabs, senior lecturer. Examiner was Anna Sjöblom, senior lecturer. All three mentioned above are active at the Department of Earth Sciences at Uppsala University.

All figures in the report are, when nothing else is mentioned, based on open access data from Swedish Meteorological and Hydrological Institute (SMHI), which comes with licensing terms specified in Creative Commons Attribution 4.0.

First of all I want to send my biggest appreciation to my supervisor Claudia for your advice, support and enthusiasm along the project. Secondly, I want to thank my subject reviewer Thomas for good discussions and input on the statistic work. I would also like to express my gratitude to Benjamin Selling, who in the beginning of my project taught me a lot about the data set and how to set up the model. Without this help it would have taken me a lot longer to start up this project. Furthermore, I would like to thank all other friends and especially Jens who supported me during this journey.

Uppsala, December 2015

Sofia Hedberg

POPULÄRVETENSKAPLIG SAMMANFATTNING

Regional kvantifiering av påverkan från klimat och mänsklig aktivitet på vattenflöden i Sverige

Sofia Hedberg

Den mänskliga påverkan på vår planets ekosystem har ökat drastiskt sedan mitten av 1900-talet. Det har gått så långt att en del vetenskapsmän talar om en ny tidsålder, antropocen (människans tidsålder). År 2000 var över 75 % av jordens markyta påverkad av mänsklig aktivitet vilket i sin tur leder till att det numera är svårt att finna opåverkade vattendrag. I detta examensarbete har orsaker till förändringar i vattenflöden i svenska vattendrag undersökts. Slutligen kunde det konstateras att variationer i nederbörd och temperatur, sammanfattat som klimatpåverkan, har större inverkan på flödesförändringar än mänsklig påverkan, såsom förändrad landanvändning.

Att förstå orsaker bakom flödesförändringar har stor betydelse för framtida vattenresurshantering och planering. En bättre förståelse om orsakerna och processerna bakom en förändring är nödvändig för att effektivt kunna vidta åtgärder och arbeta förebyggande mot exempelvis översvämningar eller tillfällig vattenbrist. Även för elproduktionen har förändringar i vattenflödet stor betydelse. Idag kommer ungefär hälften av Sveriges elektricitet från vattenkraft och att förstå vattenmängder är därför av stor vikt för kraftbolagen vad gäller planering och produktion. Förändringar i nederbörd eller markanvändning kan få inverkan på vattnets kretslopp vilket kan påverka såväl total mängd som fördelning av vattnet över årets olika delar.

Mätningar av vattenflöde har skett under lång tid i Sverige, för vissa vattendrag ända sedan slutet av 1800-talet. I detta projekt har det årliga totala vattenflödet sedan 1960-talet undersökts för ett hundratal olika vattendrag. Första delen av projektet bestod av att finna eventuella förändringar. Med statistiska test undersöktes såväl gradvisa förändringar, trender, och abrupta förändringar, det vill säga förändringar som sker tvärt. Sammanfattningsvis kan en ökande trend konstateras under 1900-talet sista hälft samt att abrupta förändringar är koncentrerade till främst 1980-talet. Att undersöka förändringar är dock inte oproblematiskt. Flödet i våra vattendrag varierar i cykler, de har alltså omväxlande perioder med större respektive mindre flöde. Vilken tidsperiod man tittar på kommer alltså att spela stor roll för den förändring som man hittar.

Efter undersökning av tidpunkter för förändringarna bestod nästa steg av att undersöka orsakerna bakom förändringarna, samt bedöma hur stor roll de olika orsakerna har. Detta gjordes med hjälp av en hydrologisk modell som förutsäger vattenflödet utifrån endast klimatvariabler som nederbörd, temperatur och avdunstning. En sådan modell kan bara beskriva förändringar som beror på klimatet men tar inte hänsyn till vad som händer i landskapet. Detta gör att skillnader i observerat och modellerat vattenflöde kan användas för att dra slutsatser om orsakerna bakom. Exempelvis om ett nytt köpcenter med en stor parkeringsyta orsakar större flöden i ett vattendrag än tidigare kommer denna förändring att kunna observeras vid mätningar i vattendragen, men inte synas i modellerade värden.

Studien genomfördes på vattendrag som enbart i liten utsträckning var påverkad av vattenkraft. I dessa vattendrag var den mänsklig påverkan i genomsnitt orsak till 7 % av den totala observerade förändringen, men sett över alla vattendrag varierade påverkan med enstaka värden från -30 och ända upp till 100 %. Ett negativt värde betyder att mänsklig aktivitet gett en flödesförändring i en annan riktning än den observerade förändringen. Exemplet med köpcentret visar att trots ett ökat vattentillskott pga. byggnationen har vattennivåerna i det närliggande vattendraget totalt sett minskat eftersom nederbördsmängden samtidigt har minskat i området.

För mänsklig påverkan kunde inga regionala skillnader, exempelvis mellan södra och norra Sverige, observeras i studien. Den slutsats som kan dras är att mänsklig påverkan på vattenflöden varierar mer mellan enskilda vattendrag än följer ett geografiskt mönster. En möjlig fortsättning på studien är att jämföra resultatet med information om historisk landanvändning och andra förändringar och se om större förändringar kan kopplas till kända händelser. En ökad kunskap om förändrade vattenflöden och orsakerna bakom är ytterst viktig för vattenresurshantering i ett framtida samhälle.

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1 INTRODUCTION

1.1 BACKGROUND

Human activities on our planet have increased dramatically since the middle of the last century (Steffen et al., 2015). Hughes et al. (2013) estimated that more than 75% of the terrestrial area had already been influenced significantly by humans in the year 2000, which makes it increasingly difficult to find undisturbed watersheds (Vogel et al., 2015). According to the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2014), the global mean surface temperature has increased by 0.72°C over the past 60 years. Around half of this change has likely been caused by human (also called 'anthropogenic') activities (IPCC, 2014), which has led some scientists to use the informal term 'Anthropocene' to denote the present time interval, in which humans alter the Earth on a scale equivalent to some of the major prehistoric events (Zalasiewicz et al., 2010).

Anthropogenic activities do not only entail anthropogenic emissions, leading to changes in the atmospheric composition. These activities also lead to land use changes that potentially modify surface albedo, surface roughness, latent heat fluxes, river runoff and irrigation (IPCC, 2014). In particular, afforestation/deforestation, the intensification of agriculture, the drainage of wetlands, road construction and urbanization are considered to have large impacts on hydrology (De Roo et al., 2001). Huntington (2006) found evidence that a changing climate combined with land use alterations contribute to an intensification of the water cycle. Similarly, Laban et al. (2004) found a significant correlation between global warming and an increase of runoff during the 20th century, while Hall et al. (2014) also mentioned relations between land use changes and changes in flood risks due to affected evapotranspiration, infiltration and water storage.

Hydrological changes form a potential threat, because water has an important role for a stable society. Both urbanization and population growth increase our dependency on water (Montanari et al., 2013). As future variations in hydrological regimes will influence future socioeconomic, ecological and climate systems, they are important to follow and understand (Vogel et al., 2015; Wagener et al., 2010). However, due to the complexity of driving forces, it is relative hard to evaluate and predict changes in streamflow regimes (Madsen et al., 2014).

Merz et al. (2012) divided drivers of hydrological changes into three groups, where the total change was described as the sum of (1) changes within the river, e.g. dam construction and regulations, (2) changes within the catchment, e.g. land use alterations, and (3) changes due to atmospheric conditions. Other studies combined the last two groups and only divided hydrological impacts into climatic and anthropogenic origins (Wang et al., 2013; Wang, 2014), although it should be noted that climate impacts are to some extend also indirectly human-driven.

Different drivers of hydrological change lead to different types of change over different time periods (Merz et al., 2012). On one hand, changes within the river (e.g., a dam construction) alter river characteristics immediately and will for example cause a step change (Figure 1.a), whereas land use changes could lead to both step changes (e.g., clear-cutting of forest) and trends (Figure 1.b), for example caused by a rather continuous transformation of agriculture land into urban areas. On the other hand, changes in atmospheric conditions (e.g., an increasing variability of precipitation) can lead to fluctuations in the streamflow variability (Figure 1.c).

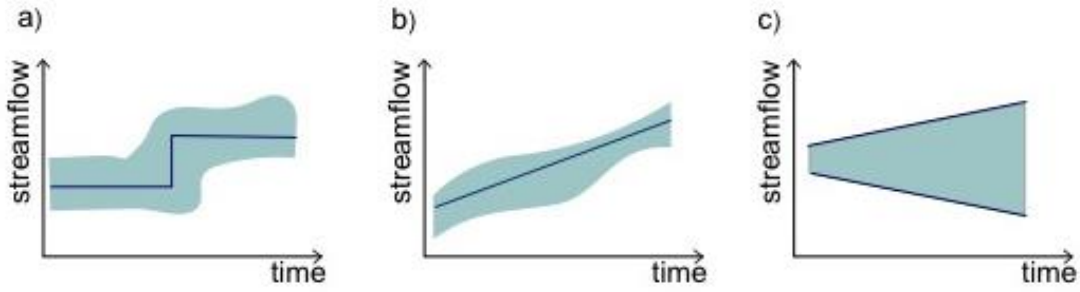

Figure 1: Different causes will give different sort of changes. In a) a step change due to e.g. clear cut. In b) a trend due to e.g. urbanization or land changes over time, c) change in variability. Redrawn after Hall et al. (2014)

Additionally, the size of a catchment and the location of change are also important factors to consider. For example, clear-cutting a specific area of forest has a greater impact on a smaller catchment compared to a bigger one. Also, impacts are expected to be larger when areas close to the measuring station are deforested. Furthermore, the driving factors also control which parts of the streamflow (e.g., low, median or high flows) change (Merz et al., 2012). Thus, streamflow changes are complex and understanding them is important for future decisions and water management in a changing environment (Wagener et al., 2010).

Studying hydrological change is not a new phenomenon (Koutsoyiannis, 2013): river levels and precipitation have been measured since historical times in several places around the world. Some of the oldest examples include water level records of the Nile already 4,000 years ago and rainfall observations around 3,100 years ago in China (Montanari et al., 2013). In recent years, however, the number of studies focusing on streamflow changes, trends and long-time behavior has considerably increased at an unprecedented rate (Hundecha and Merz, 2012; Merz et al., 2012; Szolgayova et al., 2014). To even further encourage this advancement, the International Association for Hydrological Sciences (IAHS) has dedicated the scientific decade 2013-2022 (called "Panta Rhei - Everything Flows") to research on changes in hydrology and society (Montanari et al., 2013).

The assessment of changes in hydrological regimes consists of two parts: detection and attribution. The first part, detection, is to statistically prove that a change has occurred and to eliminate the possibility that this particular change can be explained by natural variability (Merz et al., 2012). The second part, attribution, explains the causes of the detected change. There are two common methods to detect changes in observed data: (1) a data-based approach based on statistical tests, which does not require much knowledge of the physical processes in the system, but needs long data series of good quality, and (2) a data-simulation approach based on the relationship between drivers and streamflow, which allows to predict changes in the future and also to quantify differences between several different causes of change (Hall et al., 2014).

The second approach, which implies the use of hydrological models to attribute causes to changes, has gained more attention in recent years. For example, Harrigan et al. (2014) used a runoff model to compare observed and reconstructed streamflow for a catchment in Ireland. Hundecha and Merz (2012) tried to attribute changes in flood records to changes in precipitation and temperature on eight catchments in Germany. Wang et al. (2013) studied changes in streamflow in four catchments in China, where land use changes were observed as a result of the introduction of a new law in the late 1970's. These studies have in common that the number of used catchments is limited and, therefore, an analysis of regional patterns has not been possible.

This led to the idea to test the procedures for assessing changes in hydrological regimes proposed by Wang et al. (2013) on a much larger set of catchments in Sweden. The question is whether the proposed methods can also be used to detect changes and quantify their origins, even when change points are not known a priori. This project also aims at providing information as to whether the methods described in Wang et al. (2013) can be used in a broader context to detect regional patterns in climatic and anthropogenic impact on streamflow.

1.2 OBJECTIVES

This thesis aims to further develop the understanding of streamflow changes and their drivers. The objective is to quantify historical climatic and anthropogenic impacts on Swedish streams. The project consists of three parts:

1. Application of statistical tests to detect trends and change points in observed streamflow data.

2. Simulation of streamflow data (based on meteorological variables) and classification of changes depending on their different causes.

3. Investigation of regional differences in climatic and anthropogenic impacts.

2 MATERIALS AND METHODS

2.1 CONCEPTUAL IDEA

The underlying idea of this project is that the total change in streamflow (ΔQ) can be described as the sum of change due to anthropogenic impact (ΔQ_h), e.g., land use changes, and change due to climate change (ΔQ_c) (Equation 1, Figure 2).

$$\Delta Q = \Delta Q_h + \Delta Q_c \tag{1}$$

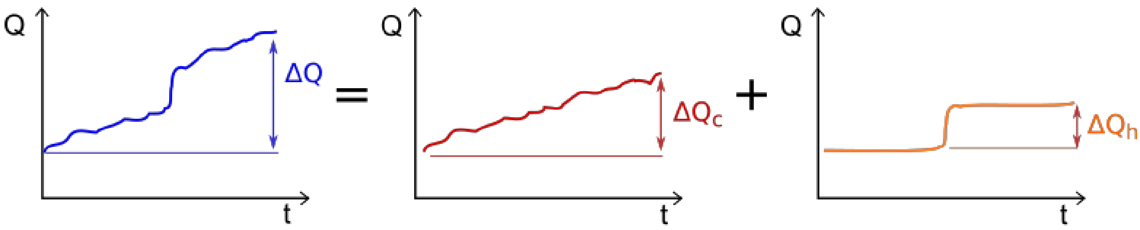

Figure 2: Exemplified separation of total streamflow change ΔQ into climate-driven change ΔQ_c and human-driven change ΔQ_h. Observe that the form of each curve should be seen as an example.

By using a simple hydrological model only driven by climate variables (e.g., temperature and precipitation), the different components of Equation 1 can be estimated, because changes in the simulated streamflow depend solely on changes in the driving climate variables, while the model does not consider anthropogenic changes. Therefore, if a catchment has not been disturbed by human activities (Figure 3a), the differences between simulated and observed values should be constant over time (Seibert and McDonnell, 2010; Wang et al., 2013). In contrast, a disturbed catchment should exhibit varying differences between simulated and observed values over time, from the time of the change point (Figure 3b).

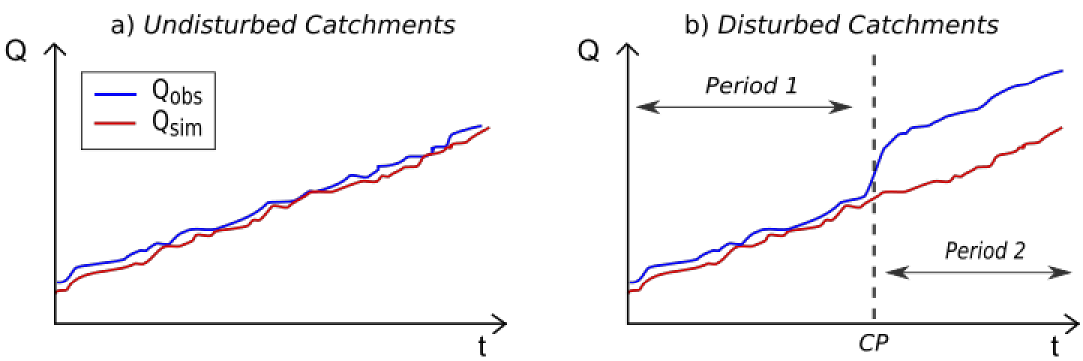

Figure 3: Synthetic example of the differences between simulated (Q_{sim}) and observed (Q_{obs}) streamflow for undisturbed (a) and disturbed (b) catchments. The dashed line marks the change point (CP).

The procedure for assessing changes in hydrological regimes proposed by Wang et al. (2013) makes use of this idea and essentially consists of the following, slightly modified, steps (cf., Figure 4):

(1) detect abrupt change points in the observed streamflow series (Figure 4a)

(2) calibrate a hydrological model before the detected change point, *period 1* (Figure 4b)

(3) simulate streamflow with the calibrated hydrological model over the entire time period (Figure 4c)

(4) correct systematic biases in the simulated streamflow so that long-term mean values of simulated streamflow match the observations during *period 1* (Figure 4d)

(5) evaluate the difference between observed and simulated streamflow before and after the detected change point (Figure 4e)

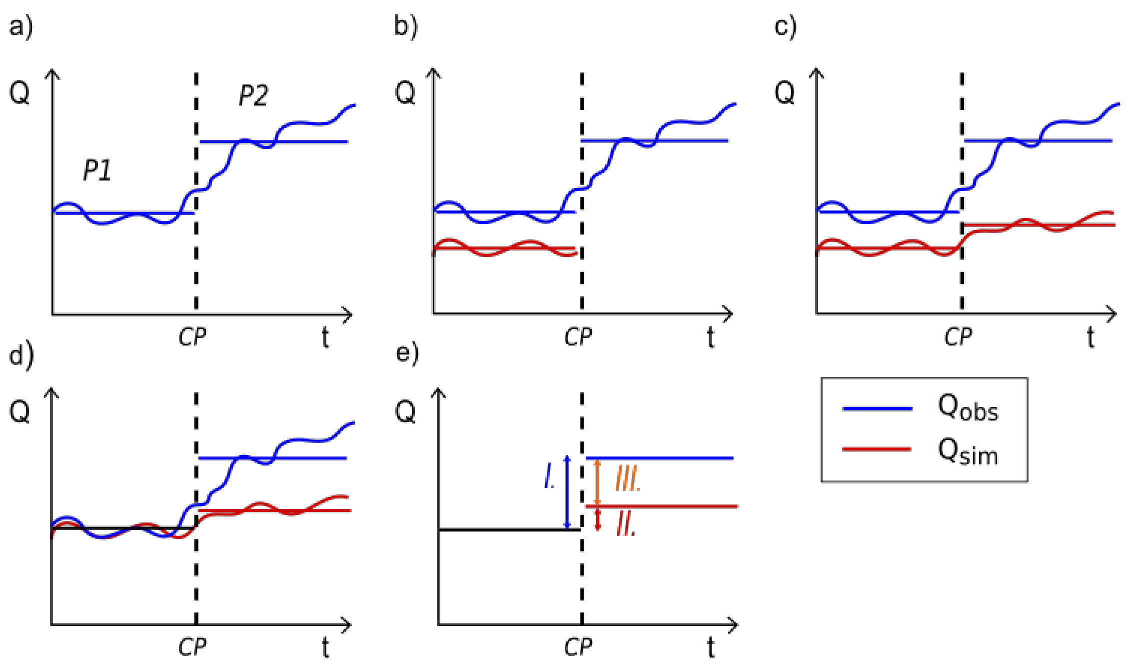

Figure 4: Schematic procedure for assessing changes in hydrological regimes in this study. The dashed lines symbolize the year of a change point (CP) that divide the time series into period 1 (P1) and period 2 (P2), the blue curves represent observed and the red curves simulated streamflow. (a) Abrupt change point detection in the observed streamflow series. (b) Calibration of the hydrological model before the detected change point. (c) Streamflow simulation over the entire time period. (d) Correction of systematic biases in the simulated streamflow so that the long-term means of observed and simulated values during period 1 are equal. (e) Comparison of observed and simulated long-term mean values. *I.* shows the difference in observed streamflow between periods 1 and 2, which represents the total change in mean streamflow. *II.* shows the difference in mean simulated streamflow between periods 1 and 2, which is the climate-driven change. *III.* shows the difference between simulated and observed streamflow during period 2, which represents the change due to human impacts.

This procedure assumes that differences in the observed streamflow (ΔQ_{obs}) between period 1 ($\Sigma Q_{obs,1}$) and period 2 ($\Sigma Q_{obs,2}$) represent the total streamflow change (Equation 2), while differences in the simulated streamflow (ΔQ_{sim}) between period 1 ($\Sigma Q_{sim,1}$) and period 2 ($\Sigma Q_{sim,2}$) are assumed to be only caused by continuously shifting driving climate variables (Equation 3) and therefore assumed to only represent the climate change impact (ΔQ_c).

$$\Delta Q = \Delta Q_{obs} = \sum Q_{obs,2} - \sum Q_{obs,1} \tag{2}$$

$$\Delta Q_c = \Delta Q_{sim} = a \sum Q_{sim,2} - a \sum Q_{sim,1} \tag{3}$$

The factor a is a term to correct for systematic errors (i.e., biases) in simulated streamflow (Equation 4). By using this multiplicative approach (so-called linear scaling), the simulated streamflow series is corrected so that the long-term mean values of simulated and observed streamflow become equal during period 1 (Figure 4d).

$$a = \frac{Q_{obs,1}}{Q_{sim,1}} \tag{4}$$

The human-driven change can then be calculated as the difference between total and climate-driven change (Equation 5, Figure 4e).

$$\Delta Q_h = \Delta Q - \Delta Q_c = \Delta Q_{obs} - \Delta Q_{sim} \tag{5}$$

All terms in Equations 2-5 refer to long-term mean values during the different periods.

2.2 DESCRIPTION OF THE AREA

Sweden (Figure 5) is boarded by mountains in the northeast and otherwise by the Baltic Sea and the North Sea. The total land area is approximately 410,000 km^2 (Statiska centralbyrån, 2015) with an extension of 500 km from east to west and 1,600 km from south to north (Jönsson and von Konow, 2015). The country has a relatively low population density compared to central Europe (Eurostat, 2015), even if the population has increased from 7.5 million inhabitants in 1960 to 9.7 millions in 2014 (Statistiska centralbyrån, 2015).

Around 65% of the land area in Sweden is covered by forest and the major agriculture areas are located in its southern parts (Arheimer and Lindström, 2015). Most of the rivers are regulated and water is typically stored during the summer to produce electricity during the winter (Lindström and Bergström, 2004). The streamflow regimes vary between different parts of the country. In south Sweden floods mainly occur during the autumn whereas the spring floods are bigger in the north due to snow accumulation (Wilson et al., 2010). Spring peaks in March to June are mainly snowmelt driven, whereas autumn floods are mainly rain driven (Arheimer and Lindström, 2015).

Figure 5: Location of Sweden, north Europe.

2.3 DESCRIPTION OF DATA

All data used, except evapotranspiration, were obtained from different databases from the Swedish Meteorological and Hydrological Institute, (SMHI). The time period used for modeling was 1961-2010, which is the period for which streamflow, precipitation and temperature data were available (Table 1). For some statistical tests, streamflow data for the period 1961-2014 were also used.

Table 1: Summary of available time series. The starting year for streamflow varies between all catchments

	Units	Temporal resolution	Available period
Streamflow	mm	Daily	~ 1961-2014
Precipitation	mm	Daily	1961-2010
Temperature	°C	Daily	1961-2010
Potential ET	mm	Monthly	1961-1978

2.3.1 Streamflow data and catchment information

Streamflow data were obtained for 324 streamflow stations (Figure 6) from the *VattenWebb* database (SMHI, 2015e). *VattenWebb* is a database that provides several types of hydrological data for free, mainly as service for local authorities (SMHI, 2014c).

The database contains, amongst others, daily measured values from 200 streamflow stations owned and operated by SMHI and additionally around 100 stations from the hydropower industry (SMHI, 2015d). For some catchments, long-term records are available, reaching back to the 19th century. For others catchments, the data series are considerably shorter. The degree of regulation (DOR) of each river, which gives the percentage of the annual streamflow that could be stored in upstream reservoirs and lakes (SMHI, 2014b), was also available from *VattenWebb*.

For each station, the corresponding catchment area was obtained as a shape file from the Swedish water archive (SVAR), which is a database maintained from SMHI with information on Swedish lakes, rivers, marine areas and catchments (SMHI, 2015a). The sizes of the catchments varied from a few square kilometers up to 5,000 km^2 but most were in the range of 100 to 300 km^2.

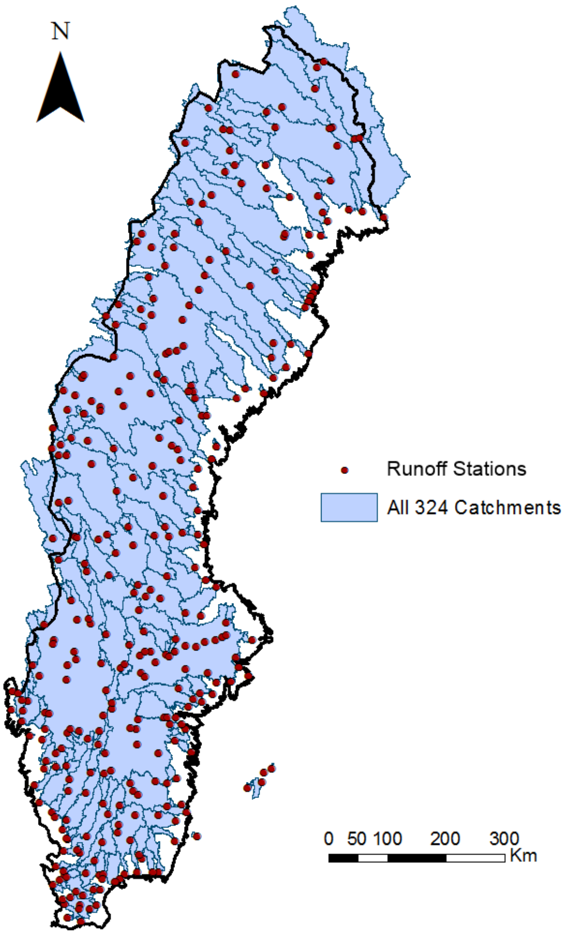

Figure 6: All 324 catchments in the *VattenWebb*. Some catchments are nested.

2.3.2 Temperature and precipitation

Temperature and precipitation data were obtained from SMHI's climate database, PTHBV (SMHI, 2015b). The database contains daily mean values of temperature and precipitation since 1961, with a resolution of 4 km x 4 km. The gridded data is based on interpolation of meteorological station data in Sweden and some stations close to the border in Norway. In the database precipitation data is corrected for measuring losses that for example can be caused by wind distribution around the instrument. To secure the quality of the data, precipitation data is controlled annually (SMHI, 2015b).

2.3.3 Potential evapotranspiration

Eriksson (1981) calculated monthly mean potential evapotranspiration (pET) for 152 meteorological stations across Sweden during the time period 1961-1978 with the Penman equation (Penman, 1948). In this project, long-term monthly mean pET (Figure 7) estimated for each catchment through Kriging interpolation was used.

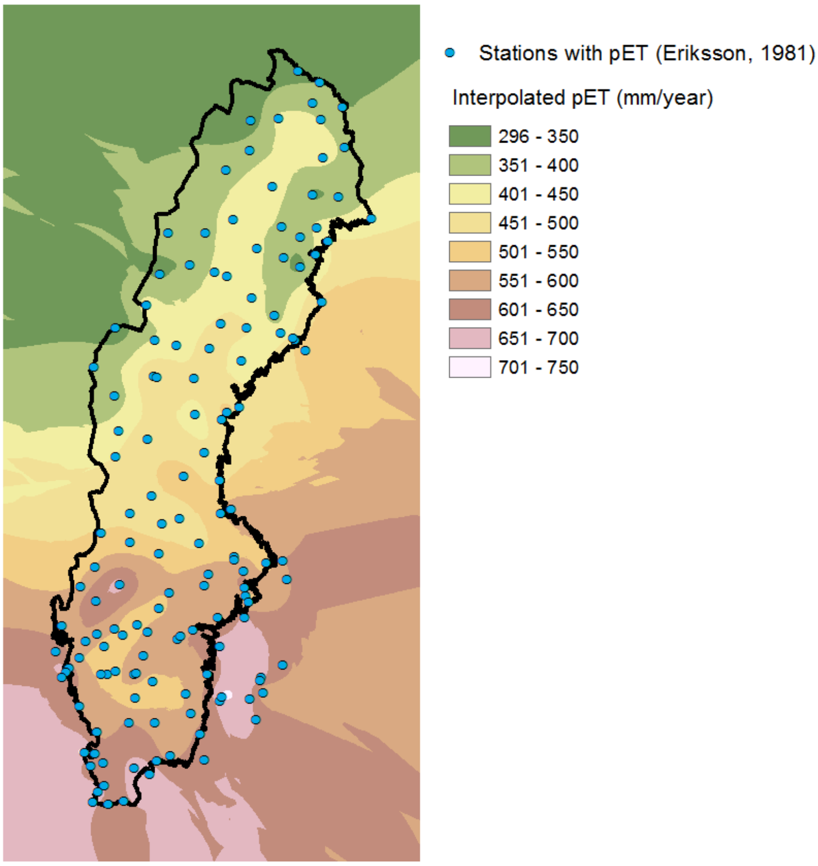

Figure 7: Map of annual potential evapotranspiration (pET) based on Eriksson (1981).

2.4 CHANGE POINT AND TREND DETECTION

The first of two main parts of the project were to detect possible change points in the streamflow data. As streamflow is rarely normally distributed (Hall et al., 2014), only non-parametric tests insensitive to the distribution of the data were applied. All statistical tests were performed for total annual streamflow values, calculated based on the hydrological year (October - September). Significance was chosen at a 10% level ($p<0.1$), which is commonly used in streamflow trend detection studies, for example by Hundecha and Merz (2012), Hall et al. (2014) and Sagarika et al. (2014).

Several of the statistical tests used in this project could only be performed with continuous data. For this reason, only streamflow series with continuous daily values between 1961 and 2014 were investigated. For gaps with less than three subsequent missing days, interpolated values were used. Single missing values were replaced with the value of the previous time step as compared to Pappas et al. (2014). Catchments with wider gaps in their streamflow records were excluded. An additional set of 40 catchments mainly located in the Scandinavian mountains along the Swedish-Norwegian border (Figure 8a), was excluded from further analysis due to water balance issues (i.e. annual streamflow exceeded precipitation), leaving in total 113 catchments (Figure 8b) for the statistical tests.

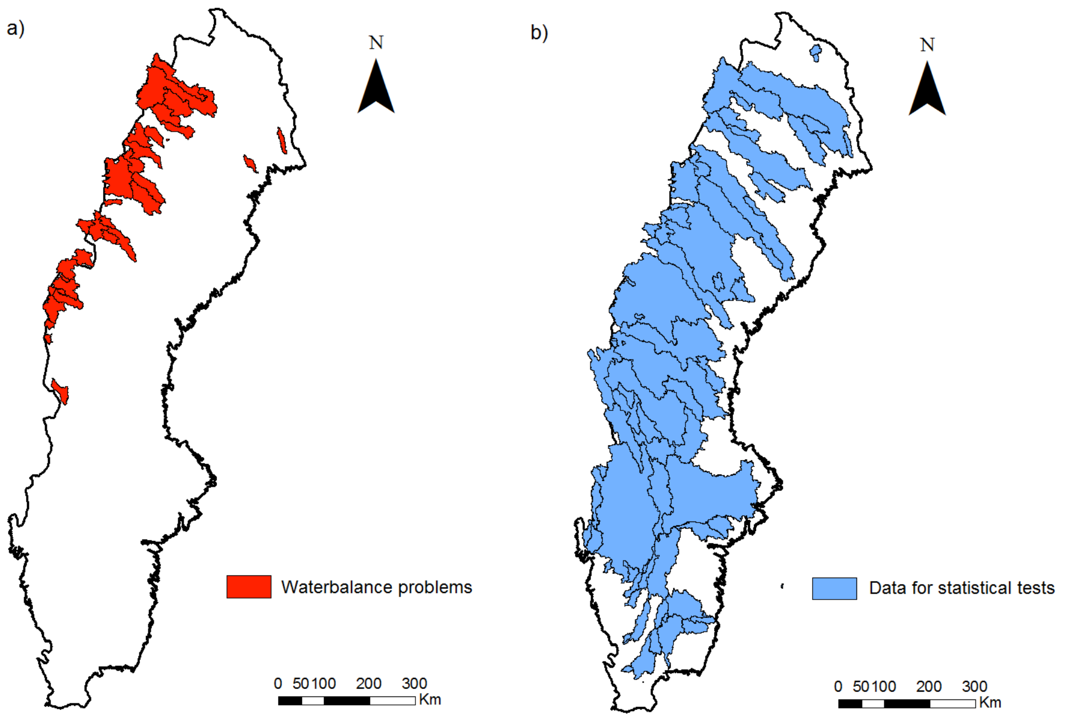

Figure 8: (a) Catchments with detected water balance issues, where streamflow exceeded precipitation. (b) Remaining 113 catchments used for statistical tests (with continuous data 1962-2010 and no water balance problems). Sub catchments are in the figure sometimes covered by nested catchments.

The results were divided into groups of north and south Sweden, in order to be able to detect regional patterns. The grouping was made from the location of the runoff station in each catchment, which mainly is the outlet. Catchments with stations north of the city of Gävle were classified as north Sweden and vice versa (Figure 9). This is a similar classification to the one used by Lindström and Bergström (2004).

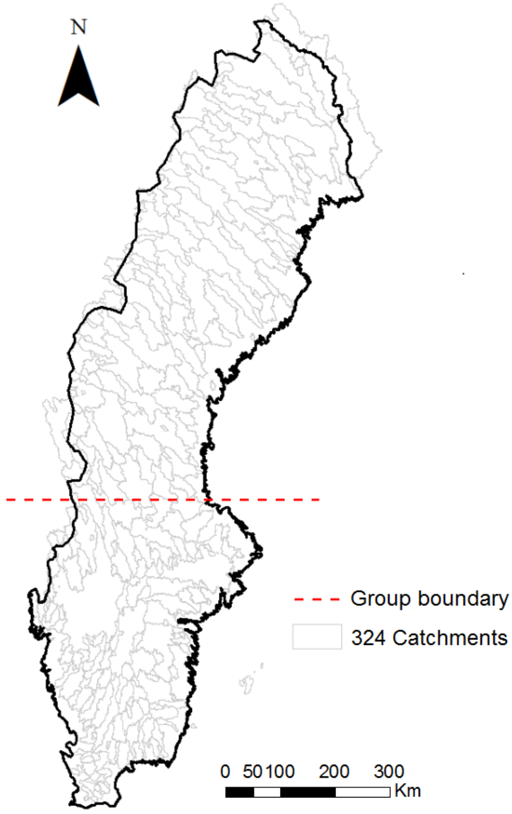

Figure 9: All catchments were divided into two groups: Northern and Southern Sweden. The boundary is in this figure marked with a red dotted line.

2.4.1 Trend detection with Mann-Kendall's test and Sen's slope

To detect trends in the streamflow records, Mann-Kendall's test (Kendall, 1975; Mann, 1945) was used. Mann-Kendall is a rank-based method (Helsel and Hirsch, 2002) that is commonly used in hydrology (Hall et al., 2014). This test uses the null hypothesis of no trend under the condition of no serial correlation (Helsel and Hirsch, 2002). Clarke (2013) assumed that the serial correlation could be neglected when investigating annual maxima of streamflow. In the present study, it is assumed that this also is convenient when using the annual sum of streamflow.

Mann-Kendall's test can only be used to detect significant trends in data sets. To further quantify trend magnitudes, the Sen's slope estimate (also known as Theil slope or Theil-Sen estimator) was used (Sen, 1968; Theil, 1992). The test estimates the slope by using the median, derived from pairwise comparisons of all points in the dataset (Helsel and Hirsch, 2002).

Further descriptions of Mann-Kendall's test and all used statistical tests can be found in Appendix A.

2.4.2 Detection of abrupt changes with Pettitt's test

For detection of abrupt changes in streamflow data, Pettitt's test was used (Pettitt, 1979). This test is a form of a rank sum test which uses cumulative sums to test the null hypothesis of no change. It divides data into two groups and investigates if they come from the same distribution (Xie et al., 2014). It is a popular non-parametric test, mostly because it is assumed to be distribution-free and insensitive to outliers and skewness in the data (Xie et al., 2014). It is often used to detect single change points in hydrological research (Wang et al., 2013; Harrigan et al., 2014; Sagarika et al., 2014), A limitation in the usability of the test is that it requires independent and detrended data (Harrigan et al., 2014). In order to detect and remove trends in the streamflow records, the above described Mann-Kendall's test and Sen's slope estimate were used.

The ability of Pettitt's test to detect a change point is dependent the position of the change point in the dataset and of the the sample size (Xie et al., 2014). For that reason, the Pettit's test was performed as a moving window test. This implies that a window of N data points at a certain starting point was chosen, and that the starting point then was shifted one year at a time. A critical task was to specify the optimal window size, as a too narrow window would lead to non-significant results and a too wide window would leave too few window sets for each time series. By implementing the Pettit's test with a moving window, it was furthermore possible to detect multiple change points in a data set, which would not have been possible by applying the test traditionally with only one window covering the entire time series.

Both the Pettitt's and Mann-Kendall's tests were performed with variable window sizes from 10 to 40 years and on the whole data set from 1962 to 2010. This period coincides in length with chosen records in many other projects (cf., studies reviewed by Wang (2014)).

2.5 ATTRIBUTION OF CHANGES

After detecting possible change points, the second step of the project was to use the climate-driven hydrological runoff model, HBV-light, in order to investigate and quantify different causes of change. To narrow the study into the given time frame the main focus was to attribute causes to abrupt changes.

2.5.1 Description of the HBV-model

The HBV-model was originally developed by SMHI and the first version came in the 1970's (Bergström, 1972). Since then, the model has been used in more than 90 countries and several different implementations have been made available (Bergström and Lindström, 2015). The implementation used in this thesis is "HBV-light version 4.0.0.9" (Seibert and Vis, 2012).

HBV is a lumped, conceptual rainfall-runoff model that simulates daily streamflow from daily precipitation and temperature data and of monthly long-term mean estimates of potential evapotranspiration. In comparison to more complex models, the need of input data is rather modest (Seibert and Vis, 2012). The model, which can be seen as a system of boxes of water, consists of four different routines and in total 15 parameters (Figure 10, Table 2). All parameters have an underlying physical meaning, but they still need to be calibrated as they represent the whole catchment and cannot be measured (Seibert and McDonnell, 2010).

The first routine, *the snow routine,* simulates snow accumulation and melt. When air temperature falls below a threshold temperature (TT), precipitation is accumulated as snow in the system. Snowmelt is then calculated by a degree-day method, where the daily melting water is controlled by a degree-day factor (CFMAX). The amount of water (melt water and precipitation) that could be stored in the snow pack is set by the parameter CWH, and the possibility that it refreezes is regulated by CFR. In the snow routine, there is also a snowfall correction factor (SFCF), which accounts for wind bias and evaporation from the snowpack. The HBV-model assumes that all runoff occurs as infiltration through the soil (Bergström and Lindström, 2015). In the *soil routine*, the fraction of the precipitation that will stay in the soil layer or continue to the groundwater is controlled by: a parameter for the maximum content of soil moisture (FC), a shape parameter (β), and a parameter (LP) that describes the actual evaporation. The *groundwater routine* consists of two boxes, an upper box with two outflows (controlled by the parameters K1 and K2) and a lower box with one outflow (controlled by the parameter K0). The amount of water that percolates from the upper to the lower box is governed by the parameter PERC. The last routine, *the routing routine*, only has one parameter (MAXBAS). It controls a triangular weighting function for transformation of the runoff.

For further details on the HBV-model, the reader is referred Bergström (2015) or Seibert and Vis (2012).

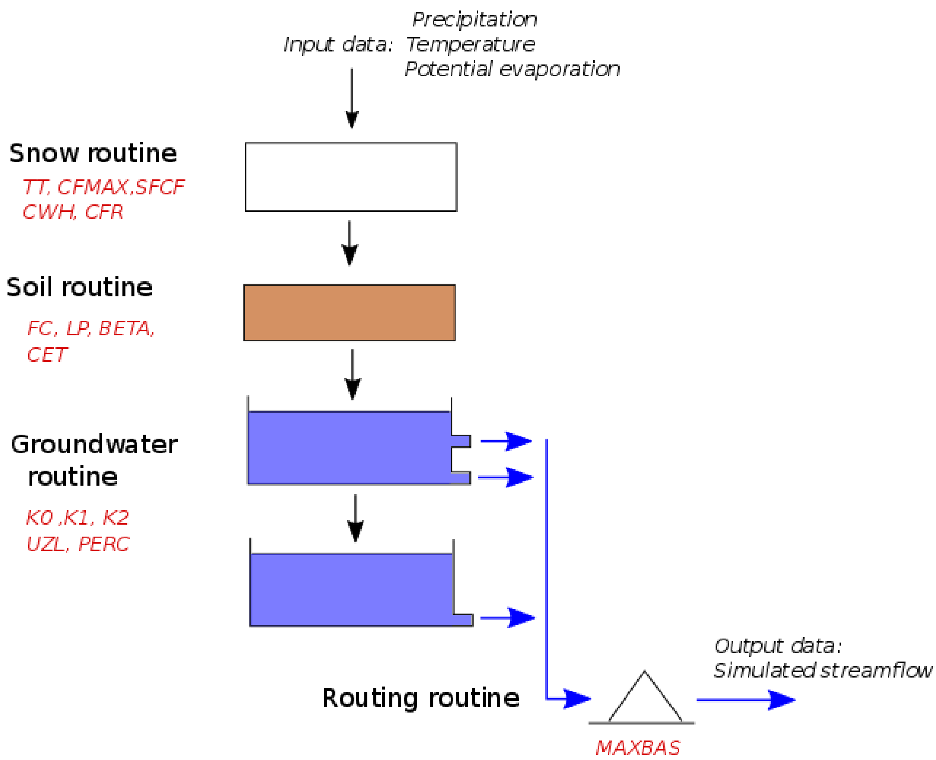

Figure 10: Conceptual structure of the HBV-model, its routines and parameters (modified from Seibert and Vis (2012)).

Table 2: Model parameters and the range (boundary values) used for the calibration. Table modified from Seibert (1999)

Parameter	Explanation	Unit	Min	Max
Snow routine				
T_T	Threshold temperature	°C	-2.6	2
C_{FMAX}	Degree-day-factor	mm °C^{-1} d^{-1}	0	7
S_{FCF}	Snowfall correction factor	-	0.4	1.5
C_{WH}	Water holding capacity	-	0	0.2
C_{FR}	Refreezing coefficient	-	0	0.25
Soil routine				
F_C	Maximum of soil moisture	mm	45	550
LP	Threshold for reduction of evaporation (SM/FC)	-	0.3	1
β	Shape coefficient	-	0.2	7
CET	Correction factor for potential evaporation	°C^{-1}	0	0.3
Groundwater routine				
K_0	Recession coefficient	d^{-1}	0.1	0.9
K_1	Recession coefficient	d^{-1}	0.005	0.6
K_2	Recession coefficient	d^{-1}	5x10^{-7}	0.15
UZL	Threshold parameter	mm	0	140
PERC	Maximal flow from upper to lower box	mm d^{-1}	0	12
Routing routine				
MAXBAS	Routing, length of weighting function	d	1	13

2.5.2 Calibration of the model

The HBV-model was only calibrated for catchments where the degree of regulation was less than 5%, in order to avoid direct impact from the power industry. Thus, the HBV-model was calibrated for only 39 catchments (Figure 11) out of the 113 catchments included in the statistical tests. A calibration period of 8 years (1962-1969) was chosen to be suitable for calibrating the HBV-model (Seibert and McDonnell, 2010). An additional year was used as warm-up period to stabilize the initial values. All catchments were considered as one unit (lumped).

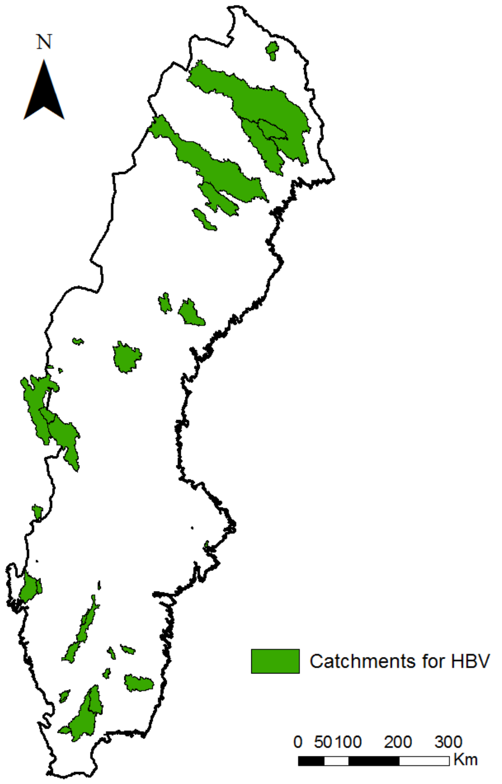

Figure 11: Overview of catchments used for hydrological modeling with the HBV-model.

To calibrate the model the built-in automatic GAP-calibration approach was used. This method is a genetic algorithm, which is using the principles of evolution to gradually evolve to a set of best fitting parameters (Seibert, 2000). Different forms of genetic algorithms are commonly used methods to effective calibrate hydrological models and to find the global maximum of given objective function (Cohen et al., 2013).

The algorithm starts with a group of *n* randomly chosen parameter sets (in this study set to 50). The parameter sets performances are evaluated and two of the parameter sets are than used to form the next set of parameters, called the next generations. The two contributing parameter sets (parental sets) are chosen based on their likelihood defined by several goodness of fit criteria: A good parameter set with a relatively high goodness of fit also has a higher chance higher to "evolve". Due to a probability constant, p', new parameters are then evolved out of parameter values from the parental sets (here p'=0.82) or out of values randomly between the parental values (p'=0.16) or are evolved as a mutation with randomly chosen values within the allowed range (p'=0.02). The process is repeated until no new parameter sets are better than those from the previous generation or until the process reaches the maximum number of possible generations (here set to 5,000).

The GAP-optimization routine in HBV-light also includes a second step after the genetic calibration, in which the results are fine-tuned (Seibert, 2000). The second step consists of carrying out a local optimization using a method called Powell's quadratic method to further improve the model fit (Press et al., 2007). Powell's method is an iterative process and was for this study iterated 1000 times.

From each calibration an optimized parameter set was obtained. The calibration was repeated several times in order to minimize the risk that a change is detected due to parameter uncertainties (Seibert and McDonnell, 2010). In total each catchment was calibrated 25 times, giving 25 different optimal parameter sets.

2.5.3 Weighted fuzzy objective function

To evaluate the performance of a set of parameters, a combination of different objective parameters was used. This approach that in Seibert (1999) is referred to as a "fuzzy measure", has the advantage that it combines the aspects of different approaches. As different objective function focus on different aspect of the model performance, they also give different goodness values for the same parameter set. The commonly used Nash-Suffcliffe efficiency, R_{eff}, (Equation 6), puts more emphasis on the fit of high flows, whereas the logarithmic efficiency, $LogR_{eff}$ (Equation 7) focuses on low flows and the volume error, *VolErr*, (Equation 8) on the total volume differences.

$$R_{eff} = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2} \tag{6}$$

$$LogR_{eff} = 1 - \frac{\sum(lnQ_{obs} - lnQ_{sim})^2}{\sum(lnQ_{obs} - \overline{lnQ_{obs}})^2} \tag{7}$$

$$VolErr = 1 - \frac{|\sum(Q_{obs} - Q_{sim})|}{\sum(Q_{obs})} \tag{8}$$

The overall model efficiency (i.e., goodness of fit) was calculated as a weighted combination of the above objective functions, with a weight of 0.6 for R_{eff}, 0.1 for $LogR_{eff}$ and 0.3 *VolErr*. For details, the reader is referred to Seibert (1999). Goodness of fit values above 0.6 were considered as behavioral models and therefore retained for further analysis.

2.5.4 Simulation and evaluation of the model performance

All sets of calibrated parameters were then used to simulate streamflow for the whole period of available data, which in total gave 25 simulated sets of simulated streamflow for each catchment for the period 1962-2010.

To evaluate the model performance before and after a change point, as described in section 2.1, periods of 15 years before and 15 years after a detected change point were compared for each catchment. For simulated streamflow the median of the 25 simulations were used for the calculations, as it would minimize the impact of a single deviant calibration set. Fifteen years is a relatively short period for comparing hydrological and climate variables, but it was also the longest time period that could be applied to catchments, due to the available data. For some catchments the time period for calibration partly overlapped with the investigated time period before change. If multiple change points were detected in a catchment, the period before the first point was compared with the period after the last point, on the condition that only a few years, at most four, differs between the detected change points.

To examine if a detected change in observed or simulated streamflow were significant, a two-sided Wilcoxon Rank Sum Test (Wilcoxon, 1945), also known as Mann-Whitney test, was used. The test uses rankings to test the null-hypothesis of no differences between two groups (Helsel and Hirsch, 2002). Differences between the period before and after a change point were investigated both for observed and for simulated streamflow, for which the median of all parameter sets were used.

2.5.5 Automation of modeling work

Even if HBV-light includes a well-developed user interface where all parameters, inputs, and outputs easily could be controlled, the model calibration as well as simulation was managed from the Windows command line. This made it possible to easily perform multiple runs and to split the catchments on different computers. Both the calibration and the simulation work were performed from the command line. A short introduction to calibration of the model using command line can be found in Selling (2015).

3 RESULTS

3.1 CHANGE POINT AND TREND DETECTION

3.1.1 Trend detection with Mann-Kendall's test and Sen's slope

The number of detected trends was strongly influenced by the chosen time period and window size. For small window sizes (i.e., shorter periods), both negative and positive trends were detected in Northern and Southern Sweden (Figure 12a,b), while almost exclusively positive trends were detected when using window sizes of twenty or thirty years (Figure 12c,d,e,f). There were no big differences between Northern and Southern Sweden. The main pattern was the same, even if a higher number of negative trends were detected in the south when using a 10 years window starting in the 60's. In the north more positive trends were detected when using bigger window sizes.

When investigating the whole time period from 1962 to 2010, only positive trends were found both in Southern and Northern Sweden. Significant trends were detected in 39% of the catchments in Northern Sweden and in 19% of the catchments in Southern Sweden.

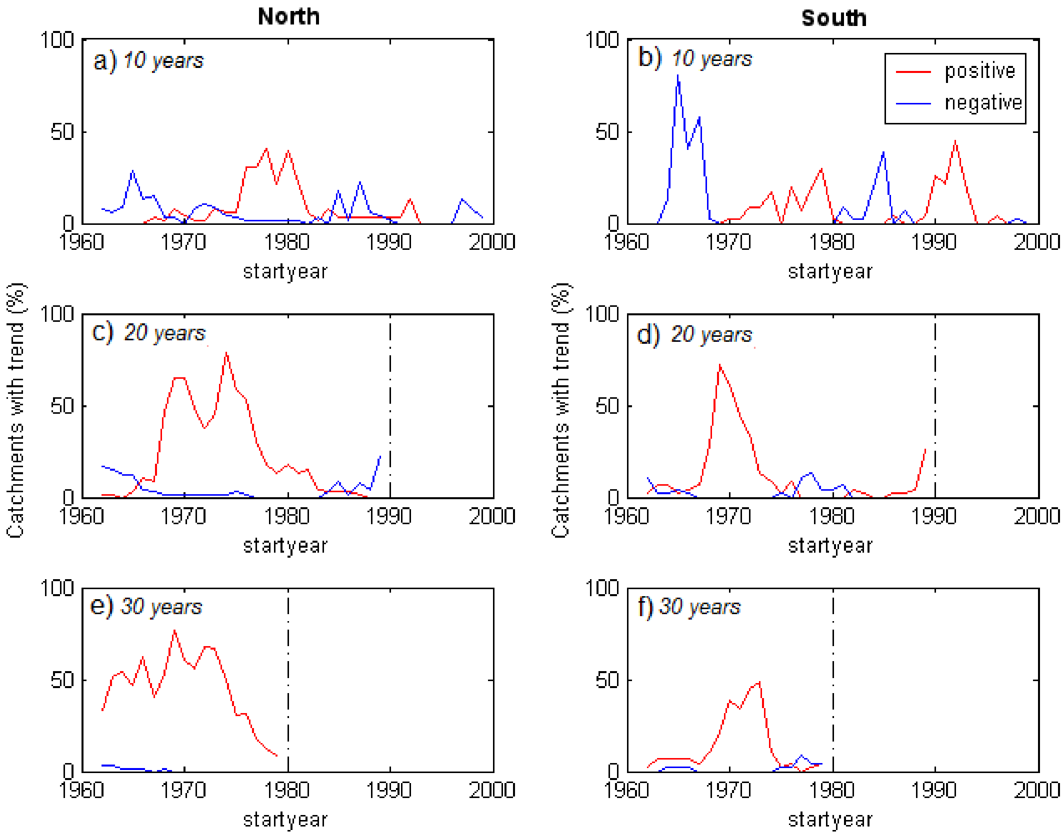

Figure 12: Number of trends detected by a Mann-Kendall test ($p < 0.1$) against start year of the used interval. In (a) and (b) a window of 10 years, in (c) and (d) a window of 20 years and in e) and f) a window of 30 years was used. The color of the lines show if the trends were negative or positive according to Sen's slope. The dotted line shows the limit for the last possible start year for investigation with the chosen window size.

The influence of the chosen time period on trend detection could also be illustrated using the data for a single catchment. For example, a significant negative trend was detected for the period 1930-1959 in the relatively long streamflow record (1930-2014) of the Grötsjön catchment in the middle part of Sweden (Figure 13). However, a positive trend was identified for the time period 1970 to 1999 while studies of the whole data set gave no significant trend at all.

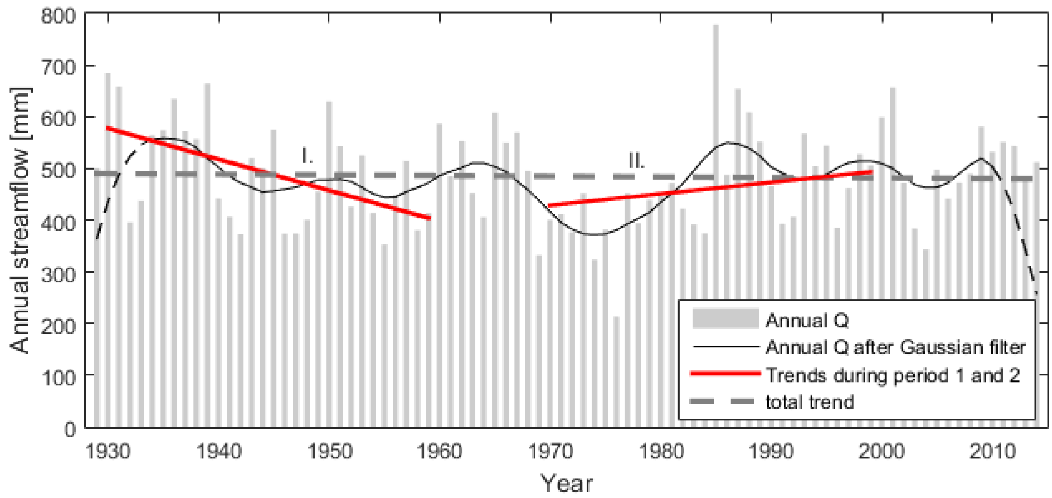

Figure 13: Trends (red lines) in annual sum of streamflow (light grey bars) for the Grötsjön catchment, Dalälven, detected during two separate time periods. Each period represent 30 years, period I from 1930 to 1959, period II from 1970 to 1999. Trends were detected with Mann-Kendalls test ($p<0.1$) and the magnitude was quantified with the Sen's slope. The grey dashed line shows the not significant slope found by investigation of the whole period. The black thin line shows Gauss-filtered values, which have been calculated based on values of ten years with a standard deviation of three years. This sort of filter smooths the signal without introducing new noise into the data (Arheimer and Lindström, 2015).

3.1.2 Detection of abrupt changes with Pettitt's test

The detection of abrupt changes was also strongly dependent on the chosen window size. More breakpoints were detected when using window sizes of 20 years or less, compared to wider window sizes (Figure 14). The differences between 20 and 30 years were considerable bigger compared to the differences between window sizes of 30 and 40 years. For further investigations with HBV, the results obtained from window sizes of 30 years were used. The reason was to avoid the periodicity detected by window sizes of 20 years and smaller. As detected change points only hardly differed between window sizes of 30 and 40 years, a window size of 30 year was considered as suitable for the following tests.

The years of identified breakpoint were clustered, with higher breakpoints frequencies during some years. A small difference between Northern and Southern Sweden was that the main peak of the number of observed breakpoints occurred earlier in the South, in 1980 compared to 1983 in the North.

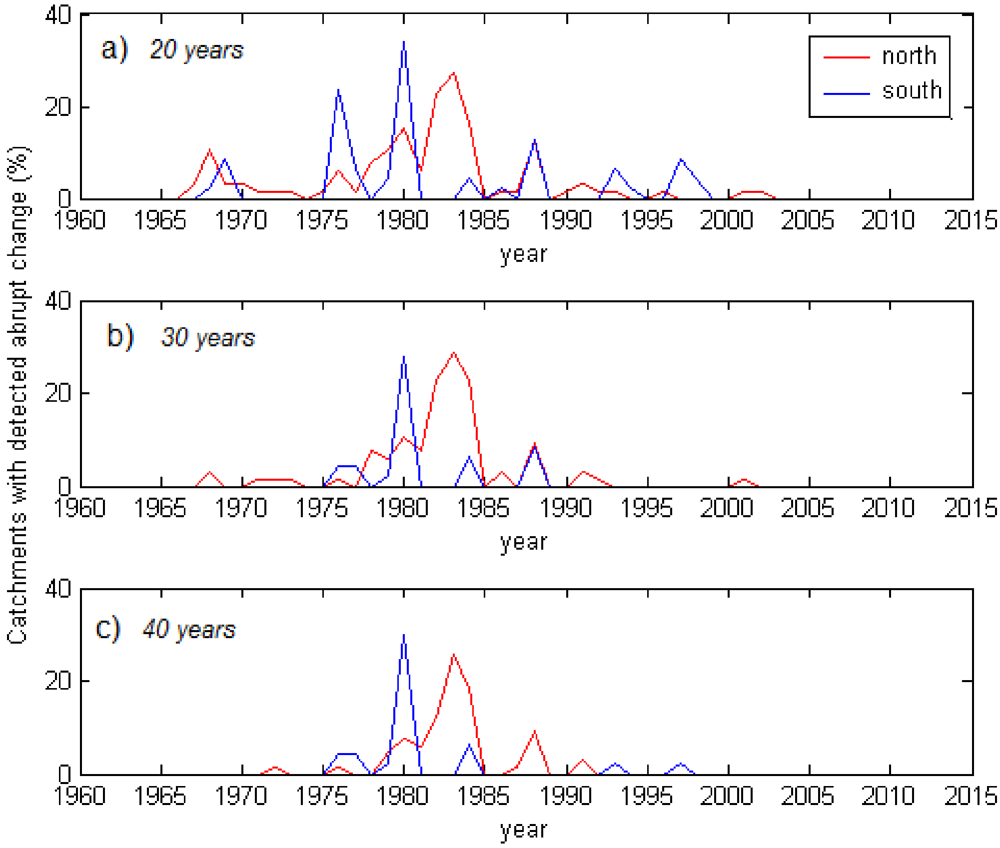

Figure 14: Change points detected by the Pettitt's test (p<0.1) with moving windows of different sizes, in (a) 20 years, in (b) 30 years and in (c) 40 years for all tested catchments. The x-axis shows the year of a detected change point, regardless of the start year of the window.

Regional patterns of breakpoints occurrence were also apparent when displayed as a map (Figure 15). In the northeast part of the country, i.e. in the mountain area, a cluster of catchments with change points occurring later than in other catchments was found.

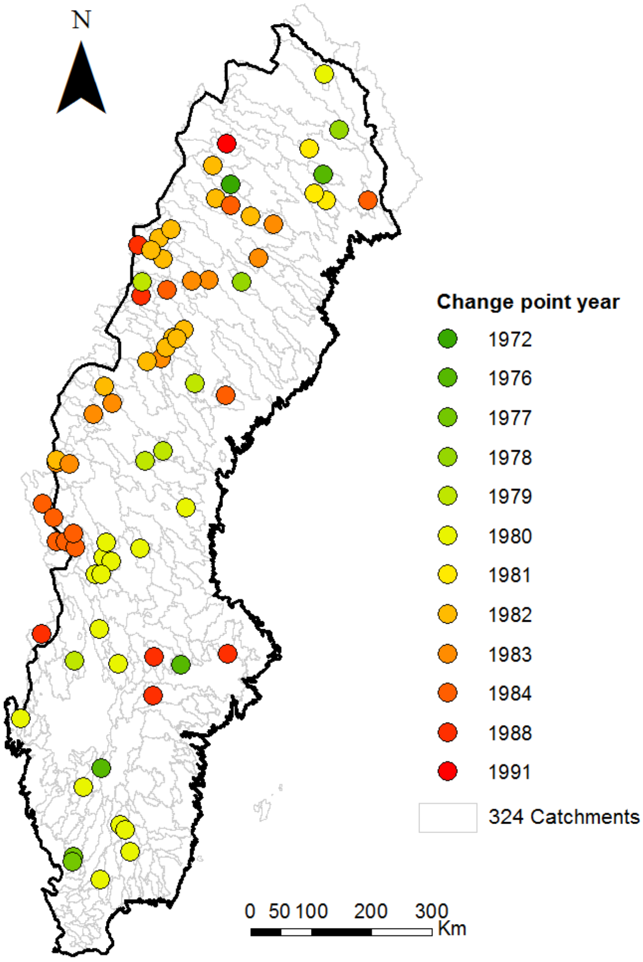

Figure 15: Change points detected with Pettitt's test (p<0.1) when investigating time series for 113 catchments and with a window size of 30 years. For catchments with multiple detected change points, the figure only shows the change point year that had the highest number of detections when varying the starting year.

Investigating the whole data set, 1962-2010, abrupt change points were detected in 16 % of all catchments in Northern Sweden (11 of 66 catchments), occurring mainly between 1982-1984 and 1991-1992. In Southern Sweden abrupt changes were detected in one of 47 catchments (2%), occurring in 1978.

3.2 ATTRIBUTION OF CHANGES

3.2.1 HBV model performance

The performance of the HBV-model calibration was acceptable for all 39 catchments. For all of them the goodness of fit was greater than 0.6, in most cases greater than 0.7, when applying the fuzzy objective function for both the calibration period and also for a validation period consisting of the direct following eight years.

3.2.2 Changes in observed and simulated streamflow

For the 39 catchments that were calibrated with the HBV-model, in total 31 significant change points were found, distributed over 23 different catchments (Figure 16). For most of them only one change point per catchment was found, but in some cases two or three different change points were detected. There were some clusters where closely located areas had change points the same year, but an obvious difference between Northern and Southern Sweden could not be found.

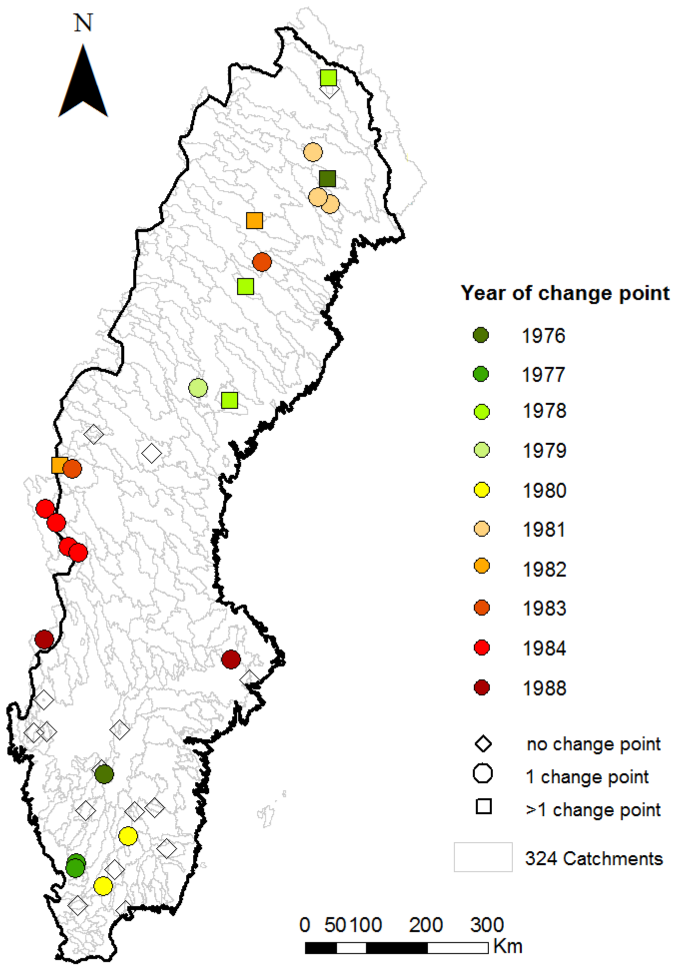

Figure 16: Year of significant change point detection by Pettitt's test: Window size of 30 years, with $p<0.1$, for the 39 catchments calibrated with the HBV-model. The color of the symbol indicates the year of a change point, in case of several change points in the same catchment the year of the first point is shown. The shape of the symbol indicates the number of change points in each catchment, filled circle=1 change point, diamond >1 change point. Observe that a non-filled circle indicates catchments without significant change point.

As described in Section 2.1 and 2.5.4, causes to detected break points were then investigated. An example of observed and simulated streamflow for one single catchment can be found in Figure 17. For this catchment, Grötsjön in the middle of Sweden, a change in both observed and simulated streamflow could be seen at the change point in 1983.

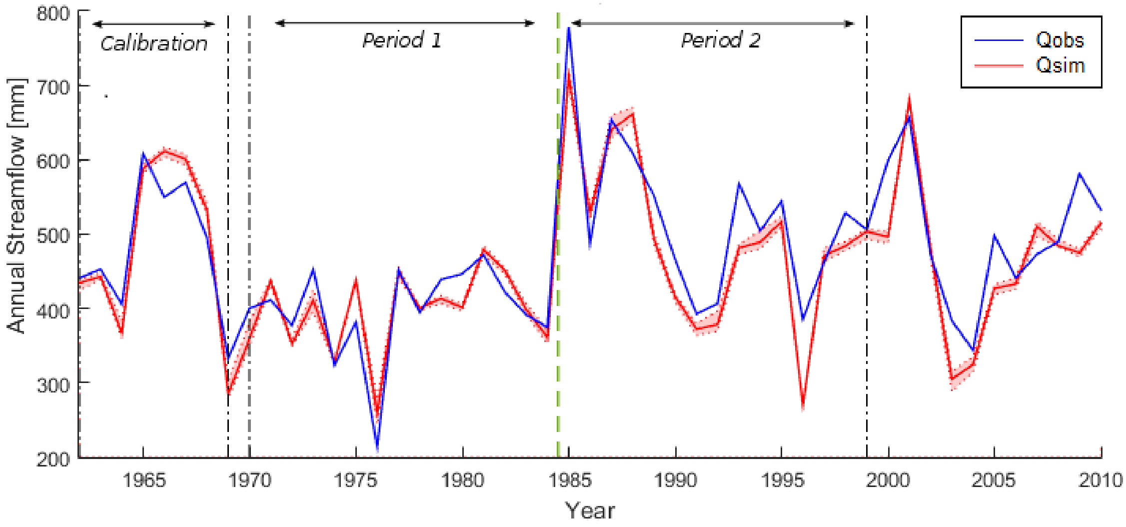

Figure 17: Observed (blue line) and simulated (red line) annual sum of streamflow for Grötsjön, Dalälven. The shaded red area shows the 25% and 75% quartile of the 25 different streamflow simulations, the red line shows the median value. The calibration period and the two periods used for differences calculations (i.e. before and after detected breakpoint) are shows within the black dotted lines. Green dashed line in the middle shows the by Pettitt's test detected change point that divide the two time periods. The simulated streamflow in this figure is not corrected with the correction term *a*.

According to a Wilcoxon Rank sum test all catchments had significant changes in observed streamflow between a period before and a period after the detected change point. The changes in observed streamflow varied between -24% and + 38% with a median of 23% (Figure 18), and with mainly positive changes except from two catchments. For simulated streamflow, significant changes between the two periods could be found in 19 catchments, when comparing the median of the 25 simulations for each catchment. The change in simulated streamflow varied between -17 and +29% with a median of 21%, but none of the negative changes was significant. The sign of the change (positive or negative) in each catchment was the same for both observed and simulated streamflow. The change in observed streamflow compared to the change in simulated streamflow varied between -8% to +21% with a median of 1%. For most catchments the differences were a few percentages, only three catchments had bigger differences.

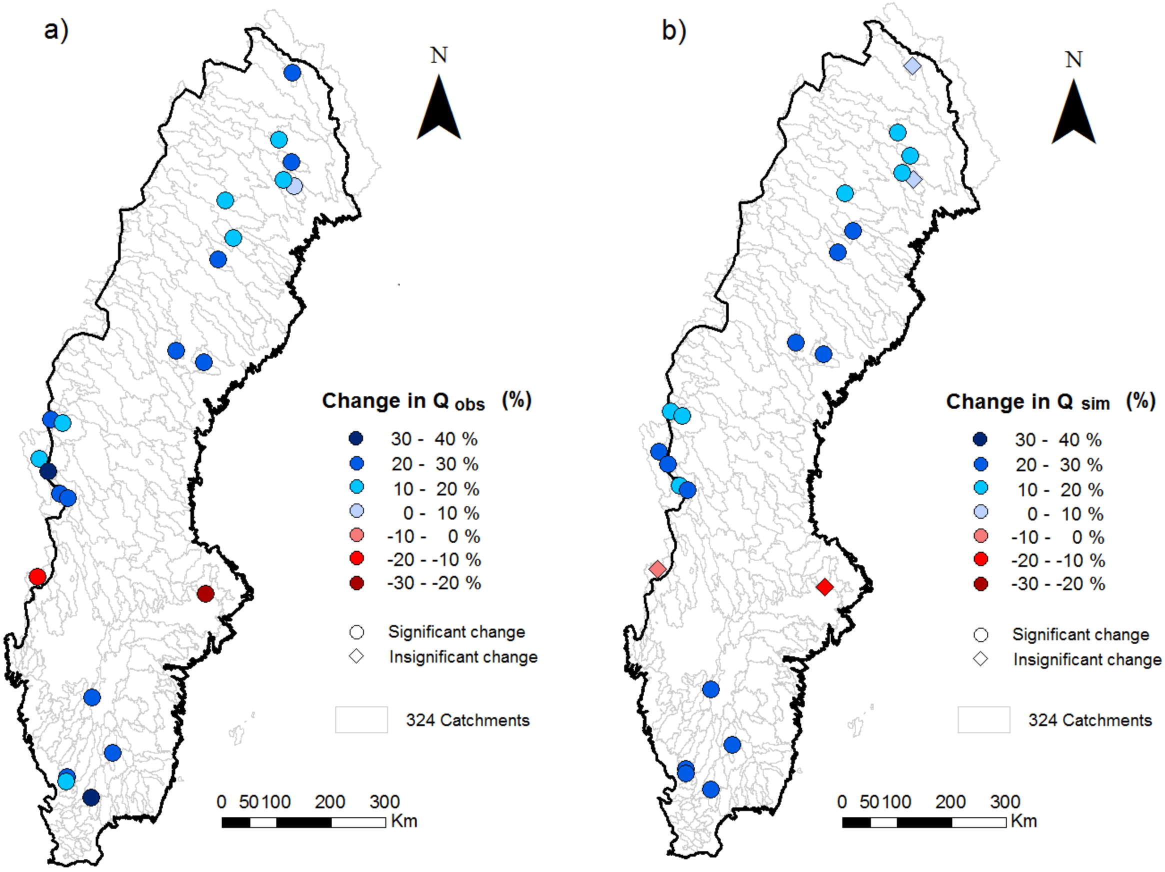

Figure 18: Changes in (a) total observed annual streamflow and (b) total simulated annual streamflow. The maps show the differences in mean values over a 15 years period before and after the change point. The colors indicate the percentage change, the shape of the symbol of the differences are significant or not at a significance level of $p<0.1$ according to Wilcoxon Rank Sum test. The map for simulated streamflow shows median values of the 25 simulations. Simulated values were bias corrected by a scaling factor *a*.

3.2.3 Climatic and anthropogenic impact on streamflow

The anthropogenic impact on the total streamflow changes varied between -29% and 98% with a median of 7% for the investigated catchments (Figure 19 and Figure 20). A negative value indicates that the human impact has led to a change in streamflow in the opposite direction than the total change. In those cases, the climatic impact on the change will be more than 100% of the total change.

The dispersion of the impact of the anthropogenic change for the 25 parameter sets is visualized by a box plot (Figure 20). The Interquartile range (IQR) varies from a few percentages to up to 20%, with no clear regional pattern.

No obvious regional differences could be seen by studying either a map of catchments centroids (Figure 19) or a plot with x-coordinate for the catchment station, i.e. mostly the outlet of the catchment (Figure 20).

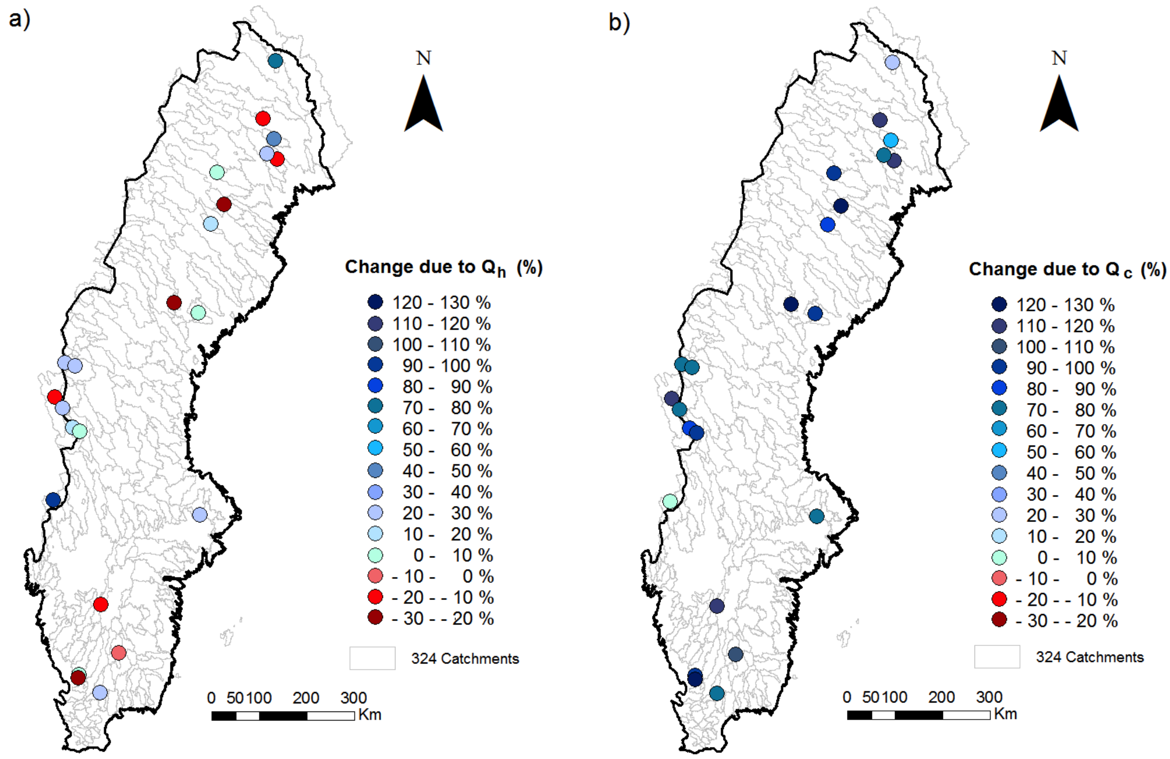

Figure 19: (a) Percentage of total change in streamflow that could be explained by anthropogenic changes in, Q_h and (b) percentage that could be explained by changes in climatic changes, Q_c.

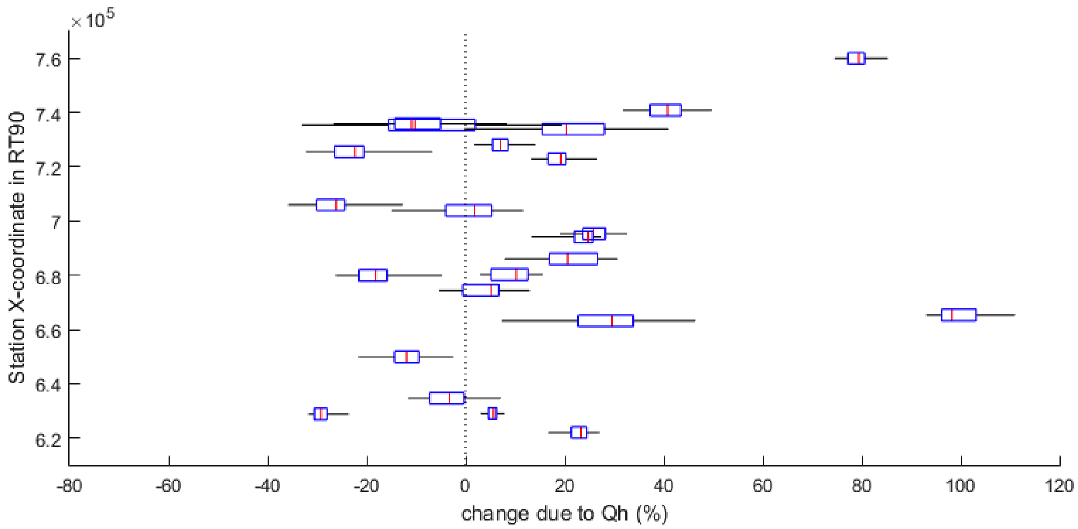

Figure 20: Anthropogenic impact on streamflow changes as percentage of the total change. Boxes show median, 25%- and 75%-percentile of 25 different simulation sets. The black line shows the whole extend, from minimum to maximum values for each catchments. The x-axis shows the X-coordinate of the catchment station (outlet), which means that catchments in the north are found in the top of the figure (station).

4 DISCUSSION

4.1 STATISTICAL TESTS AND THE PROBLEM OF PERIODICITY

The found of periods of higher presence of positive respectively negative trends when using window sizes of ten years, indicates that streamflow oscillates between wetter and drier periods. By applying a Gaussian filter to representative data for a single catchment (Figure 13), this pattern can be illustrated. For that particular catchment, the cycles have a periodicity of around 15 to 25 years with wetter and drier periods of circa 10 years each. Cycles in runoff are a known phenomenon. It was at first investigated by Hurst (1951), by studying time series of the streamflow in the Nile. Since then it have been detected in several streams around the world (Hall et al., 2014). In Sweden, cyclic variation in runoff has been observed in for example maximum annual streamflow (Arheimer and Lindström, 2015). In general these oscillating behavior is not fully understood even if there are some ideas that they might occur due to climate-ocean oscillations (Hall et al., 2014). However, the investigation of the origin of those oscillations is beyond the scope of this project and has not been further investigated.

This kind of fluctuations occurs on different time-scales from some years and up to centuries (Koutsoyiannis, 2003). For annual streamflow in Sweden these fluctuations seems to be short enough to be cancelled out when using a time interval of twenty years or bigger. Another possible explanation is natural variability, which will be cancelled out and disappear when using a bigger window. In a recent review article on flooding trends, Hall et al. (2014) suggested that research in the future should focus on detection of wet and dry periods instead of trend detection.

4.2 FOUND CHANGES AND COMPARISON TO EARLIER STUDIES

The results from the change detection part, see Section 3.1, are mainly in agreement with earlier studies (Lindström and Bergström, 2004; Wilson et al., 2010; van der Velde et al., 2013). That negative trends were found in Southern Sweden between 1960-1970 in when using a small window size (10 years) are in agreement with Lindström and Bergstöm (2004) who described the 70's as an especially dry decade. In contrast, the present study could not find the same pattern in the Northern part of the country. The detection of mainly positive trends when using bigger window sizes agrees with previous studies as well. During the last part of the 20th century there was, at least at a relatively small time scale, an increase in streamflow in large parts of Sweden (Lindström and Bergström, 2004; Wilson et al., 2010; van der Velde et al., 2013). This is related to that the last two decades in the 20th century are considered to have been unusually wet (Lindström and Bergström, 2004) and especially in northern Sweden an increase in streamflows has been seen during this time (Wilson et al., 2010).

Change points in the mountainous area seem to occur later than in the other catchments. A possible explanation could be a delay due to water accumulation. By comparing Figure 8 and Figure 11, it can be seen that most of these catchments are excluded from the modeling part due to high degree of regulation. Storage of water could possibly cause a delayed response to changes. Since a considerable part of precipitation falls as snow in the northwestern areas (SMHI, 2014a), also snow accumulation could be an influencing factor. Another possible explanation is differences in the driving variables for the change.

4.3 THE PROBLEM OF SPATIOTEMPORAL AUTOCORRELATION

The used methods do not takes spatial correlation into account and, thus, there is a risk for bias. If a trend is detected in one catchment, trends are often also detected in near situated catchments (Wilson et al., 2010). In the present study this was observed for abrupt changes (Figure 15). As the spatial distribution of catchments is irregular, this leads to problem when comparing different regions with each other (Wilson et al., 2010). If a trend is detected in a catchment with many closely located catchments, the impact on the result could be bigger than if a trend was detected in an area with a lesser catchment density.

Another issue related to correlation is temporal autocorrelation. The assumption of no serial correlation in annual sum streamflow could be questioned. In a study on annual mean flow, Harrigan et al. (2014) found that a positive correlation have large impact on the result. Presence of serial correlation could lead to false rejection of the null-hypothesis (Sagarika et al., 2014), which means detection of a non-existing trend. Of that reason temporal autocorrelation should be eliminated before applying the statistical tests, for example by using a pre-whiting filter (Wilson et al., 2010; Harrigan et al., 2014; Sagarika et al., 2014).

4.4 ATTRIBUTION OF CHANGES

For most of the investigated catchments the climatic impact on streamflow changes is greater than the anthropogenic influence. In comparison to the results from Wang (2013), where three of four investigated catchments were mainly effected by anthropogenic activities, the found anthropogenic impact was smaller. A possible explanation is that Sweden is less densely populated compared to the investigated areas in China, which probably leads to a smaller anthropogenic pressure on natural resources. Another explanation is a change in local legislation, which led to big land use changes in China. During the investigated time frame, similar changes in legislation have not been integrated in Swedish law. Therefore, comparable sharp changes are not expected.

There are two catchments that stand out from the rest, with an anthropogenic impact of almost 100% of the total change. It is one catchment in Northern Sweden (Torneälv) and one catchment in Southern Sweden (Göta Älv). No specific differences according area or lake percentage could be found. However, it is hard to speculate about why these two catchments stand out from the rest. At least Torneälv is located in an area where land use changes could be considered to be relative small. It is reasonable that the anthropogenic impact probably originates from changes within the river, either the water path is partly changed or there are changes in regulation regimes. The degree of regulation was used in order to exclude regulated catchments, although there are some concerns about the accuracy of this dataset. When comparing the degree of regulation for each catchment with the position of known hydroelectric power stations, the data do not always seem to be in agreement with each other.

A limitation of this study is that attribution of causes is only performed for stream with a low degree of regulation because their runoff response is easier to model. As the waterpower industry is considerable in Sweden, this implements that catchments with presumed high anthropogenic impact were excluded from the analysis. Of that reason the result could be consider to be biased. A future step should be to include regulated catchments and compare the degree of regulations with the anthropogenic impact on each catchment.

4.5 REGIONAL DIFFERENCES TO CAUSES

No clear regional pattern in anthropogenic and climatic impacts was found. A possible reason is that anthropogenic impact, e.g. land use changes, may vary more between individual catchment than following a regional pattern. Arheimer and Lindström (2015) stated that a noisy spatial pattern could make it hard to detect general regional changes, and that changes due to climatic impact could be greater for individual rivers compared the whole country. One question for the future is if a regional pattern could be seen when studying bigger areas, for example different regions in Europe.

It is possible that bigger differences may be detected by studying other hydrological indicators such as annual minimum flow, spring peak or monthly values. Several earlier studies have reported changes in the annual cycle of streamflow (Bergström et al., 2001; Andréasson et al., 2004; Arheimer and Lindström, 2015), some examples are decreased spring floods and increased autumn flow (Andréasson et al., 2004). Lindström and Bergström (2004) stated that extreme values seem to change more than annual means.

In a study where the HBV-model together with climate scenario series were used to investigate climate impact on runoff in Sweden, Bergström et al. (2001) found bigger model uncertainties in Southern Sweden and suggested that this might have been caused by higher evaporation and lower runoff coefficients. In the present study however, no higher variability between different parameters sets in Southern Sweden was found (**Figure 20**). It is possible that variability between different parameters sets are more dependent on each individual catchments, e.g. on catchment area, location of the change in the catchment or the quality of data for that catchment.

4.6 METHODOLOGICAL UNCERTAINTIES

Finally, there are some further concerns regarding the method and the input data that should be addressed. Firstly, the time periods used in this project may be too small to address the topic of climate change. Normally, reference periods of 30 years are used for comparison of different climatic periods (IPCC, 2014; SMHI, 2015c), but due to the length of the available data this could not be done in this project. The notion "climatic impact" is used throughout this report, but the reader should be aware of the limitations. Secondly, changes in the stream during the record time, could influence the reliability of the streamflow data. SMHI uses water levels and rating curves to determine streamflow and although that data is reconstructed when the rating curve is updated, the possible impact of the uncertainties in the data is considered to be relatively big (Arheimer and Lindström, 2015). At last, the choice to compare the period before the first change with the period after the last change, when multiple changes are present in catchment, has the disadvantage that it does not capture changes between those change points.

4.7 FURTHER RESEARCH

Kundzewicz and Robson (2004) asserted that change detection studies are not complete without a deep exploratory data analysis. For studies like Wang et al (2013), when studying a few number of catchments with change points expected at a specific time, this will not be a major problem. In those studies, statistical tests are used to prove the existence of a change point instead of finding its position, which leads to that periodicity is not a major problem. When studying a small number of catchments, it is possible to use visual inspection to detect patterns in streamflow and to detect potential additional change points. Natural variability (i.e., the occurrence of wet and dry periods) becomes a big problem when searching for change points in a bigger number of catchments. A comprehensive work was done in the beginning of this study to understand and know the data behind, but even more research is needed to really understand the data and to validate the results. This is also not unproblematic, as the biggest challenge probably is to define what to search for and evaluate.

A main problem for investigation of regional differences was that a relatively limited number of catchments were used in the end for attribution of changes. Here follows some suggestions for future research, which could increase the number of investigated catchments.

- Use more catchments for the modeling part, for example by also using catchment with a higher degree of regulation. Lindström and Bergström (2004) stated that only few reservoirs store water for more than one year, and meant that those time series should be useful for investigations of annual sums (but not extremes).
- Compare a larger number of different periods. One suggestion would be to compare two freely chosen periods, regardless of detected change points. This could for example be done by investigating the differences between the wet period in the 1970's and the dry period in the 1980-1990 (Lindström and Bergström, 2004). Can all differences be explained by natural variability?
- By using the results from smaller window sizes from Pettitt's test, there are a higher number of change points that could be used. An interesting aspect to investigate is how the used window size would influence the results. Is the obtained anthropogenic impact bigger or smaller when using change points detected by a smaller window size?

A further natural step would be to compare change points and anthropogenic impact to records of land use changes, regulations records and so on. A major limitation for carrying out this step is inadequate and insufficient data. In other studies lack of information about urbanization and land cover changes are often a big a concern (Harrigan et al., 2014). In some cases data do not exist and in other it would probably take a long time to collect and put it together. Harrigan et al. (2014) stated that the lack of information should be seen as opportunities for future research. They claim that attribution of hydrological changes is challenging but that it is even more important to understand the interaction between anthropogenic and natural hydrological changes.

5 CONCLUSIONS

The anthropogenic impact in was found to be smaller than the climatic impact on streamflow changes in Sweden in catchments with a low degree of regulation (5 %). The obtained median value for human impact was 7% of the total change in observed streamflow. Two catchments stand out with an anthropogenic impact of almost 100%, but the causes to the high values are not understood. The impact of anthropogenic activities on streamflow is low compared to what was identified in the similar study of four catchments in China. The differences could be explained by a lower population density in Sweden and the lack of legislation changes during the investigated time period. A major bias for the results is that streams with a higher degree of regulation were excluded.

No regional differences in anthropogenic and climatic impact were found. The anthropogenic impact varies between catchments, but does not show a clear regional pattern. To clearly state the absence of regional differences, further investigations on a larger number of catchments is needed. Better understanding of the data behind, and also to involve more catchments, are needed for improvements for future studies. A possible additional step would be to compare the results with other information and time series for each catchment.

In the change detection part of this study it was identified that streamflow varies in cycles, with periods of drier and wetter years. For change detection, this becomes a problem as the result becomes highly dependent on the chosen time frame. When using smaller window sizes (10 years) periods with alternating positive respectively negative trends were detected, whereas mostly positive trends were found with bigger window sizes (20 or 30 years). An increased streamflow during the late 20th century is in agreement with previous studies on Swedish streamflow. Abrupt changes were mainly found in the beginning of the 1980's. In that period significant change points were detected in almost 30 % of all catchments. No obvious regional patterns could be found in trends or in abrupt changes. For bigger window sizes, positive trends were detected under a slightly longer time period and change points seems to occur some years later in the mountain areas in the North-western part of the country compared to then surrounding areas. For future change point detection analysis in the future, a step that handles spatiotemporal autocorrelation should be included into the method to avoid the risk of detecting non-existing changes.

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APPENDIX A – Description of the statistical tests

MANN-KENDALL'S TEST

The Mann-Kendall test statistics, S, are based on a comparison of different observation (Equation 9), here describes as in (Yue et al., 2002; Sagarika et al., 2014)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{9}$$

where x_i and x_j represents individual observations and n are the total length of the dataset. The sign-term is defined as in Equation 10.

$$sgn(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{10}$$

For $n \geq 8$ there is a standardized version of the test, assuming that S in this case is approximately normal distributed with a mean value, $E(S)=0$ and a variance, $V(S)$, calculated as in Equation 11

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \tag{11}$$

where t_i is the number of ties of extent i. From this, the Mann Kendall standardized test statistics, Z, is calculated, see Equation 12,

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & S < 0 \end{cases} \tag{12}$$

and then the two-sided probability value, p, can be estimated from

$$p = 0.5 - \Phi(|Z|) \tag{13}$$

where

$$\Phi(|Z|) = \frac{1}{\sqrt{2\pi}} \int_0^{|Z|} e^{-t^2/2} dt \tag{14}$$

SEN'S SLOPE

Sen's slop is used to quantify the slope of a detected trend. Here described as in Yue et al. (2002)

$$b = Median\ \frac{x_j - x_i}{j - i} \quad \forall\, i < j \tag{15}$$

where b is the slope of the trend and x_i and x_j are individual observations. The results are used to detrend data before applying Pettitt's test.

A detected slope is then removed from the data (Equation 16) before applying Pettitt's test.

$$x_i' = x_i - b(x_i - x_1) \tag{16}$$

PETTITT'S TEST

For continus data sets, there is a simplified approximation of test (Pettitt, 1979) here presented as in Xie et al. (2014). The method is based on a statistical index $U_{t,T}$, which could be calculated as a recursive function (Equation 17)

$$U_{t,T} = U_{t-1,T} + V_{t,T} \tag{17}$$

where T is the complete number of samples and t the observation number of a potential change point. The additive term $V_{t,T}$ is calculated as a sum of the signs from comparing different pairs of observations for $j=2,\dots,T$ (Equation 18)

$$V_{t,T} = \sum_{j=1}^{T} sgn(x_j - x_t) \tag{18}$$

where the sign term is defined as in equation 10 and $U_{1,T} = V_{1,T}$

The most likely change point in the dataset is detected as the maximum of the absolute value of the statistical index $U_{t,T}$ (Equation 19)

$$K_T = \max_{1 \le t < T} |U_{t,T}| \tag{19}$$

The probability that the detected point is a real change point is than estimated from the maximal statistical index value and the total number of observations (Equation 20)

$$p = 2\exp\left(\frac{-6K_T^2}{(T^3 + T^2)}\right) \tag{20}$$

Which is an approximation of the two-sided p-value that is only satisfied for small probability values, $p<0.5$ (Pettitt, 1979).

WILCOXON RANK SUM TEST

As for the Mann-Kendall test, normal distribution of the data could be assumed for larger sample sizes. For Wilcoxon each group should consist of more than10 samples. In those cases could the mean value and standard deviation can be used for an approximation of the test (Helsel and Hirsch, 2002) as in equation 21 and 22,

$$\mu_W = n(N+1)/2 \tag{21}$$

$$\sigma_W = \sqrt{nm(N+1)/12} \tag{22}$$

where n and m are the sample size of each group and N is the sum of those two. The standardized test statistics, Z_{rs} are than computed as in equation 23,

$$Z_{rs} = \begin{cases} \dfrac{W_{rs} - \frac{d}{2} - m_W}{s_W}, & if\ W_{rs} > m_W \\ 0, & if\ W_{rs} > m_W \\ \dfrac{W_{rs} - \frac{d}{2} - m_W}{s_W}, & if\ W_{rs} > m_W \end{cases} \tag{23}$$

where W_{rs} is the sum of ranks of the group with the smallest size.