W 13 034

Examensarbete 15 hp
December 2013

UPPSALA
UNIVERSITET

SLU

Assessing the impacts of climate change on runoff along a climatic gradient of Sweden using PERSiST

Utvärdering av klimatförändringars effekt på avrinningen längs en klimatgradient

Tobias Salmonsson

Abstract

Assessing the impacts of climate change on runoff along a climatic gradient of Sweden using PERSiST

Tobias Salmonsson

Climate change is a well-studied subject but large uncertainties still exist in future projections. These uncertainties are even larger on future runoff projections at catchment scales due to the differences in local landscape factors. Continuous assessments are therefore needed to improve our understanding and increase our preparedness for the future. One way forward is to assess the impact of climate change on runoff with the new hydrological model PERSiST. PERSiST was calibrated to four study catchments that spread out along a south-north climate gradient of Sweden. The model well simulated the stream discharges with Nash-Sutcliffe values ranging from 0.55 to 0.76. The model was then driven by downscaled and bias-corrected weather data (2061–2090) from an ensemble of 15 Regional Climate Models. The runoff projections showed that the impact of climate change on runoff would differ across the catchments. All catchments would see an increase in annual runoff with the greatest increase in the northernmost catchment. The northernmost catchment would also see a likely decline in spring flood, a shift in timing of the spring flood from May to April and an increase in winter runoff. As a result of an increase in winter runoff, there could be a loss of seasonality. In the more southern catchments the present-day runoff was more evenly distributed during the year and the projected loss of seasonality was not as pronounced. The conclusion was that the impact of climate change on runoff would increase northward, due to the higher response to climate change in the northernmost catchments.

Keywords: Climate change, runoff, PERSiST, climatic gradient, spring flood

Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Box 7050, SE-750 07 Uppsala, Sweden

Referat

Utvärdering av klimatförändringars effekt på avrinningen längs en klimatgradient av Sverige med hjälp av PERSiST
Tobias Salmonsson

Klimatförändringar är ett välstuderat ämne men stora osäkerheter kvarstår vad gäller framtida projektioner. Dessa osäkerheter är ännu större när det kommer till framtida projektioner av avrinning på grund av stora olikheter i lokala faktorer. Därför är fortsatta utvärderingar av nytta för att öka förståelsen och förbättra förberedelsen för framtiden. Ett steg i rätt riktning är att utvärdera klimatförändringars effekt på avrinning med hjälp av den nya hydrologiska modellen PERSiST. PERSiST kalibrerades för fyra olika avrinningsområden som var utspridda längs en syd-nord-gradient av Sverige. Den kalibrerade modellen simulerade det observerade flödet med Nash-Sutcliffe värden från 0,55 till 0,76. Modellen kördes sedan med nerskalad och bias-korrigerad väderdata (2061–2090) från en ensemble av 15 regionala klimatmodeller. Resultatet visade att klimatförändringars effekt på avrinning varierade mellan avrinningsområdena. Alla avrinningsområden påvisade en ökning i total årlig avrinning. Den största ökningen stod att finna i det nordligaste avrinningsområdet. Det nordligaste avrinningsområdet påvisade även en trolig minskning i vårflodsvolym, en skiftning av vårfloden från maj till april samt högre flöden vintertid. Som ett resultat av högre flöden vintertid uppstod en minskning av säsongsvariation. I de sydligare avrinningsområdena var dagens flöden jämnare fördelade över året, vilket gjorde att minskningen av säsongsvariation inte var lika stor. Slutsatsen var att klimatförändringarnas effekt på avrinning ökar norrut.

Nyckelord: Klimatförändringar, avrinning, PERSiST, klimatgradient, vårflod

Institutionen för vatten och miljö, Sveriges lantbruksuniversitet (SLU), Box 7050, SE-750 07 Uppsala, Sverige

Preface

This degree project has been carried out as the final 30 credits of the Master Programme in Environmental and Water Engineering. The project has been accomplished with Dr. Stephen Oni as supervisor and Dr. Martyn Futter as subject reviewer, both at the Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences.

I would like to thank my supervisor Dr. Stephen Oni for great advices throughout the project and subject reviewer Dr. Martyn Futter for valuable input and for helping me to conceptual figures and understanding of the PERSiST model. I would also like to give my thanks to Dr. Claudia Teutschbein at the Department of Physical Geography and Quaternary Geology, Stockholm University, for providing downscaled and bias-corrected climate data for the study sites. Also, thanks to Lantmäteriet for providing a free and open map service.

UPTEC W 13 034, ISSN 1401-5765
Published digitally at Department of Earth Sciences, Uppsala University 2013

Populärvetenskaplig sammanfattning

Utvärdering av klimatförändringars effekt på avrinningen längs en klimatgradient av Sverige med hjälp av PERSiST

Tobias Salmonsson

Forskarna är överens om att vi står inför en pågående klimatförändring och otaliga studier har gjorts för att analysera och värdera de möjliga utgångarna. Detta är mycket viktigt för att öka förståelsen och möjligheten till förberedande åtgärder. När det kommer till att förutsäga hydrologiska framtidsförhållanden kvarstår dock stora osäkerheter. Fortsatta studier inom området är av stor vikt för att öka trovärdigheten och begränsa osäkerheten. Ett steg i rätt riktning är att studera de framtida hydrologiska förhållandena med en ny hydrologisk modell. I det här arbetet har just detta gjorts och valet av modell har fallit på PERSiST. PERSiST är en nyutvecklad modell som simulerar flödet i en eller flera punkter i ett vattendrag. Allt som krävs för att köra modellen är tidsserier av temperatur och nederbörd. Därifrån kan sedan modellen kalibreras för att ge ett flöde som liknar det observerade flödet i vattendraget. I det här arbetet kalibrerades modellen för fyra olika avrinningsområden i Sverige; Aneboda, Gårdsjön, Kindla och Krycklan. De fyra avrinningsområdena var utspridda längs en klimatgradient av Sverige för att ge möjligheten att värdera och jämföra klimatförändringarnas effekt på platser med skilda klimat. Aneboda och Gårdsjön är de avrinningsområden som ligger längst söder ut och visar det varmaste klimatet. Gårdsjön är dessutom det avrinningsområde med mest nederbörd. Kindla ligger i centrala Sverige och har under vintern ett mer utbrett snötäcke än Aneboda och Gårdsjön. Det kallaste klimatet och mest utbredda snötäcket hittar vi dock i det nordligaste avrinningsområdet Krycklan.

När PERSiST var kalibrerad för det fyra områdena krävdes framtida tidsserier av temperatur och nederbörd för att simulera de framtida hydrologiska förhållandena. Den erhållna framtida klimatdatan sträckte sig från 2061-2090 och kom från en samling av 15 olika klimatmodeller. Att använda 15 olika framtidsscenarion skapade ett brett urval av scenarion där det sammanräknade medelscenariot troligtvis faller närmare verkligheten än vad ett enskilt scenario skulle göra. Klimatdatan från klimatmodellerna hade skalats ner från en regional skala med för grov upplösning för att appliceras direkt på de studerade avrinningsområdena. Alla 15 scenarion för alla fyra avrinningsområden kördes sedan genom PERSiST för att skapa 15 olika hydrologiska framtidsscenarion för varje område. Dessa framtidsscenarion utvärderades sedan som ett medelscenario, ett max-scenario och ett min-scenario utav avrinning.

Det visade sig att alla tänkbara scenarion pekade mot en förlust i säsongsvariation i både Krycklan och Kindla. Förlusten var inte alls lika påtaglig i de södra avrinningsområdena Aneboda och Gårdsjön. Av alla fyra områden är det Krycklan som idag visar den tydligaste och största vårfloden. Framtidsscenariot visade en mycket tydlig skiftning i Krycklans vårflod. Vårfloden kommer att uppträdda en månad tidigare, i april istället för maj, och den kommer även att minska enligt medel- och min-scenariot. Detta kan tillskrivas den höjda temperaturens inverkan på snötäcket. Följden av en ökad temperatur blir ett mindre konstant snötäcke som smälter oftare och tidigare under vintern. Detta skapar också en märkbart större avrinning under vinterhalvåret. För avrinningsområdena Aneboda, Gårdsjön och Kindla visade klimatdatan för 2061-2090 att perioden med minusgrader skulle försvinna helt och hållet. Detta återspeglade sig i de hydrologiska simuleringarna på så sätt att den relativt lilla vårflod som tidigare uppvisades i Aneboda och Kindla helt försvann.

Alla avrinningsområden i studien visade en procentuell ökning i årlig avrinning. Ökningen var störst i Krycklan och detta tillsammans med förlusten i säsongsvariation i Krycklan ledde till slutsatsen att norra Sverige är den del av landet där den hydrologiska effekten av klimatförändringar kommer vara störst. Ur ett hydrologiskt perspektiv kommer platser med mycket snö alltid vara känsliga för en ökad temperatur. Snön innehåller nämligen en lagrad vattenekvivalent som snabbt kan skapa nya förutsättningar. Många studier har tidigare påvisat att effekten av klimatförändringar kommer vara störst på nordliga breddgrader. Simuleringarna gjorda med PERSiST underströk detta ytterligare.

1. Introduction

Climate change has been a subject of research in the natural and social scientific community in the last few decades (Stehr and Von Storch, 1994, McCabe and Wolock, 1997). The Intergovernmental Panel on Climate Change (IPCC) has predicted a rise in global mean temperature of 1.1-6.4 °C by the year 2100 (Solomon et al., 2007). The effects of climate change have been predicted to be larger in high latitude countries such as Sweden (Tetzlaff et al., 2013, Laudon et al., 2013). This change in climate would bring a future with new precipitation patterns and water regimes (McCabe and Wolock, 1997). Change in precipitation patterns will have large implications on catchment water balance due to intensification of extreme hydrologic events (Chou et al., 2013). However, our preparedness for future change associated with change in precipitation patterns is low as large uncertainties exist in our present capability of precipitation projections (Allen and Ingram, 2002). This is because most simulations of precipitation by Global Climate Models (GCMs) do not agree well with observed precipitation (Teutschbein and Seibert, 2012b). As a result, there are large uncertainties and unknown implications on the future water regimes. However, changes in the water regime could largely impact human livelihood, including both the drinking water supply and hydropower reservoir operations and electricity generation (Crossman et al., 2012, Oni et al., 2012a). Continuous assessment of hydrological responses to a future climate is therefore necessary to constrain the large uncertainty in our projections and to devise mitigation measures for extreme events.

One way to assess a possible range of future runoff conditions at a catchment scale is to use an ensemble of climate projections (Teutschbein and Seibert, 2012b). This approach has been shown to constrain the inherent uncertainty in future projections by GCMs (Murphy et al., 2004), as a range of possible climate impacts would be explored instead of projection based on a single GCM (Oni et al., 2012b). Furthermore, GCMs are based on global scale atmospheric variables and due to regional differences and variation in local factors; they are too coarse for direct application at local catchment scales (Teutschbein and Seibert, 2012b). Therefore, downscaling helps to transfer the GCM or Regional Climate Model (RCM) data to a higher resolution (Teutschbein and Seibert, 2012b). Several downscaling techniques (such as statistical and dynamic downscaling) have been used in climate impact studies (Fowler et al., 2007). However, climate model output may still carry bias error and not agree with observed weather data. Therefore various bias correcting approaches have been used (Teutschbein and Seibert, 2012b) to help the impact modeller gather reliable climate data.

The Swedish Meteorological and Hydrological Institute (SMHI) has extensively studied hydrologic effects of climate change in the Nordic region. The impact of climate change on water resources in the Nordic region has been found to have much in common with the impact in the rest of Europe (Bergström et al., 2001). As a result of warmer climate, snow cover will be reduced due to less stable winter conditions and spring flood less dominant during spring snowmelt (Bergström et al., 2001, Andréasson et al., 2004). In regions with an extensive snow cover, spring flood is a main hydrological event during the year and strongly affects both fresh water supplies and ecosystem health (Stewart et al., 2004).

The hydrological effects of climate change in Sweden have been widely assessed using Hydrologiska Byråns Vattenbalansavdelning (HBV) rainfall-runoff model (Bergström et al., 2001, Andréasson et al., 2004). Understanding how climate change impacts hydrologic conditions across the gradient of Sweden requires the use of several hydrological models with different conceptualizations but comparable to HBV. One way forward is to test a new catchment scale hydrological model across the climate gradient of Sweden. This thesis will assess the impact of climate change on runoff using PERSiST (Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport). One advantage of using PERSiST is that the model has a very flexible model structure and can give a good representation of the modeller's perceptual idea of the underlying structure (Futter et al., 2013).

The impact of climate change on runoff was explored using an ensemble of regional climate models (RCM) projections, driven by different GCMs. The expectation was that the study could provide a range of plausible impacts of climate change on runoff conditions across a climate gradient (south-north and west-east) of Sweden. This objective would be achieved as the study sites are spread out in these directions. The delimitations of this study can be attributed to the fact that 1) only one site will represent the south, only one will represent the east etc. and 2) the sites characteristics will be assumed to stay constant in time. The overall goal to assess the impact of climate change along a climate gradient of Sweden was achieved using the following steps:

- Calibrate PERSiST for the study sites.
- Run the calibrated model with climate change scenarios for the study sites.
- Evaluate the impact of climate change at the study sites.
- Evaluate the impact of climate change along a climate gradient.

2. Materials and Methods

The general method was to calibrate PERSiST for the study sites using observed data for temperature and precipitation, and then run the calibrated model using future climate change scenarios. The simulated future runoff scenarios were then assessed in contrast to the observed runoff of the present day.

2.1 Study Sites

Long term monitoring of ecosystems can benefit the society by providing detailed knowledge on the cause and effect of different processes. As a result, Swedish Environmental Protection Agency (SEPA) established fifteen Integrated Monitoring (IM) sites in 1981 where biological and chemical indicators were monitored (Löfgren, 2002). Later in 1994, it was decided to focus the monitoring efforts on four sites instead of fifteen. The four sites chosen were small and homogeneous catchments both in terms of geology and vegetation cover. Other criteria for selection of the four sites included 1) the neighbouring catchments should be homogeneous to eliminate any border effects and 2) the sites should be well defined hydrologically. The resulting four Swedish IM sites include Aneboda, Gårdsjön, Kindla and Gammtratten headwater catchments. The catchments are located along a south-north climate gradient (Figure 1).

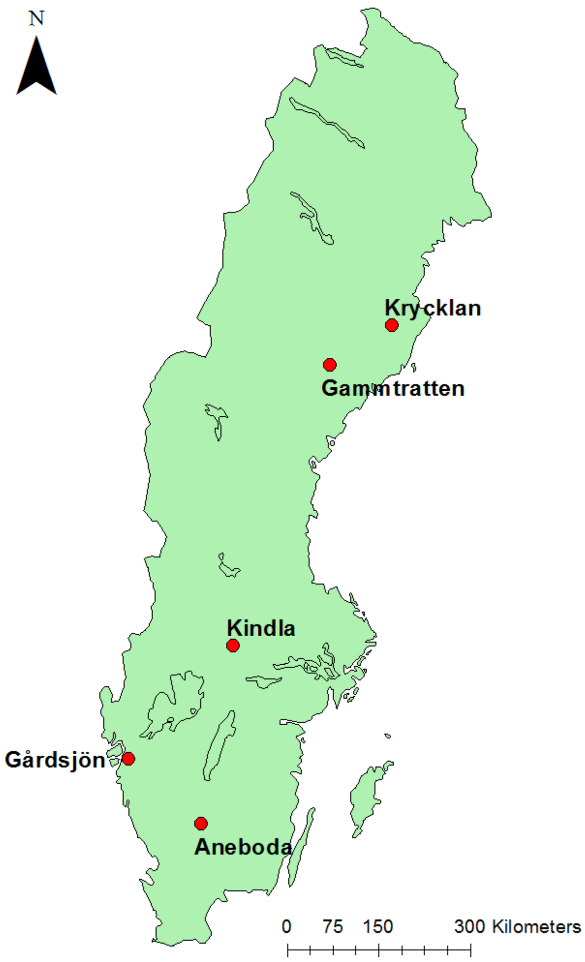

Figure 1. Location of the four IM sites and Krycklan catchment along a south-north gradient of Sweden. ©Lantmäteriet

Today the IM sites have benefitted from long term monitoring of air, streams and soils to understand the effects of long-range transboundary air pollution in soil water, groundwater and surface water (Löfgren, 2002). Therefore the catchment characteristics of these catchments are well known and documented. The spreading of the catchments along a climate gradient of Sweden made the four IM catchments well suited for this study. However, due to error in the Gammtratten weather data that was corrected too late, future scenarios in this catchment could not be driven. Runoff projections were instead made for Svartberget catchment, a nested subcatchment in Krycklan catchment. Since Krycklan catchment is in close proximity to Gammtratten and has similar characteristics, the switch was viable without compromising the goal of assessing climate change effects along a south-north gradient. More information about the studied catchments and their attributes follow.

2.1.1 Aneboda Catchment

Aneboda is a headwater boreal catchment (57°07′ N, 14°03′ E) located in the province of Småland. The catchment area was about 18.9 ha and represents the most southernmost of the four IM sites. The elevation of the catchment ranged from 210 – 240 meters above sea level (m.a.s.l). The land cover consists of 82% dry forest and 18% wet spruce or open mire (Futter et al., 2011). The vegetation is dominated by Norway spruce and soil types in the catchment was dominated by till (79 %) (Löfgren et al., 2011, Futter et al., 2011). There is almost no bedrock outcrop (<1%) and the bedrock geology is granite (Löfgren et al., 2011, Futter et al., 2011). Annual mean air temperature (1996–2008) of the catchment is 6.5 °C and mean annual precipitation (1996–2008) was 800 mm/year. However, only about 8% of this total precipitation fell as snow (Futter et al., 2011). The average duration of snow cover in the catchment was 110 days (Winterdahl et al., 2011). The average annual runoff (1997–2008) was 280 mm/year (Winterdahl et al., 2011). In January 2005, Aneboda was hit by the storm Gudrun. The storm caused substantial damage to the forest and afterwards a lot of woody debris covered the ground. This was followed by bark beetle infestation, causing even more damage to the forest vegetation (Löfgren et al., 2011).

2.1.2 Gårdsjön Catchment

Gårdsjön is a headwater catchment (58°03′ N, 12°01′ E) that is located in the province of Bohuslän. This is the westernmost of the four IM sites. The elevation of the catchment ranges from 114 – 140 m.a.s.l. The catchment (3.6 ha) consists of 84% dry forest, 11% wet spruce or open mire and 5% other land covers (Futter et al., 2011). Norway spruce is the dominating tree species and till (63%) represents the dominating soil type in the catchment (Löfgren et al., 2011, Futter et al., 2011). The bedrock geology is granite with significant bedrock outcrop (34%) (Löfgren et al., 2011, Futter et al., 2011). Annual mean air temperature (1996–2008) was 7.0 °C and annual mean precipitation (1996–2008) was 1110 mm/year. Only about 7% of the total precipitation in the catchment fell as snow (Futter et al., 2011). The average duration of snow cover was 55 days (Winterdahl et al., 2011). The average annual runoff (1989–2008) was 570 mm/year (Winterdahl et al., 2011). The January 2005 storm Gudrun also hit Gårdsjön but was much less severe compared to Aneboda (Löfgren et al., 2011).

2.1.3 Kindla Catchment

Kindla headwater catchment (59°45′ N, 14°54′ E) is located in Örebro County in the middle of Sweden. The elevation ranges from 312 – 415 m.a.s.l. The catchment drains an area of 20.4 ha and the land cover consists of 71% dry forest, 24% wet spruce or open mire and 5% other land covers (Futter et al., 2011). Norway spruce is also the dominant tree species with till soil type (56%) (Löfgren et al., 2011, Futter et al., 2011). There is also significant bedrock outcrop (41%) of the underlining granite

(Löfgren et al., 2011, Futter et al., 2011). Annual mean air temperature (1996–2008) was 5.2 °C and annual mean precipitation (1996–2008) estimated as 850 mm/year. Almost 21% of the total precipitation fell as snow (Futter et al., 2011). The average duration of snow cover was 130 days (Winterdahl et al., 2011). The average annual runoff (1997–2008) was 423 mm/year (Winterdahl et al., 2011).

2.1.5 Svartberget Catchment

Svartberget is a headwater boreal catchment (64°23′ N, 19°78′ E) located in close proximity to Gammtratten catchment. The catchment is nested within Krycklan study catchment in northern Sweden, approximately 60 km northwest of Umeå city. The catchment area measures 50 ha and is dominated by forest and mire, the forest consists of Norway spruce and Scots pine (Oni et al., 2013). Till of varying thickness is the most common soil type and beneath lies a gneissic bedrock geology (Oni et al., 2013). Annual mean air temperature (1996–2008) was 2.4 °C and annual mean precipitation (1996–2008) was 635 mm/year, of which 35–50% falls as snow (Oni et al., 2013). The average duration of the snow cover is 170 days and the average annual runoff was 320 mm/year (Oni et al., 2013). Svartberget catchment is referred to as Krycklan throughout the thesis.

2.2 Data Analysis

2.2.1 Historical Data

The temperature and precipitation time series for the IM sites were continuous and had daily values from 1st January 1996 to 31st December 2008. Krycklan had longer term series of temperature and precipitation from 1981 to 2012. However, only the 1996–2008 period was used to make it comparable with the IM sites. Unlike weather data, stream discharge was not continuous throughout the study period in all study sites. The gaps varied in length and were too large to be replaced by mean values of contiguous time steps. This was particularly noted in Aneboda and Kindla.

Annual mean temperature and annual precipitation for 1996–2008 were subject to a graphical analysis to illustrate the climatic difference between the study sites. To illustrate and compare the seasonal patterns of runoff at the study sites, monthly discharge was calculated and divided by the average of all months. This normalisation made it possible to compare the study sites' different seasonal runoff patterns with each other.

2.2.2 Future Climate Data

Climate models are applied as a tool for climate predictions. However, predicting a local climate scenario for small catchments requires downscaling. Downscaling is a method that derives local- or regional-scale scenarios from larger-scale models. Though the accuracy of this method depends on the quality and resolution of the larger-scale model (Teutschbein and Seibert, 2012b). In this study, 15 different RCMs that were driven by different GCMs under A1B scenario were used (Table 1).

Table 1. The ensemble of RCMs with driving GCMs used to derive the provided climate data

No.	Institute	RCM	Resolution	Driving GCM	Scenario
1	C4I	RCA3	25 km	HadCM3Q16	A1B
2	DMI	HIRHAM5	25 km	ARPEGE	A1B
3	DMI	HIRHAM5	25 km	BCM	A1B
4	DMI	HIRHAM5	25 km	ECHAM5	A1B
5	ETHZ	CLM	25 km	HadCM3Q0	A1B
6	HC	HadRM3Q0	25 km	HadCM3Q0	A1B
7	HC	HadRM3Q3	25 km	HadCM3Q3	A1B
8	HC	HadRM3Q16	25 km	HadCM3Q16	A1B
9	KNMI	RACMO	25 km	ECHAM5	A1B
10	MPI	REMO	25 km	ECHAM5	A1B
11	SMHI	RCA	25 km	BCM	A1B
12	SMHI	RCA	25 km	ECHAM5	A1B
13	SMHI	RCA	25 km	HadCM3Q3	A1B
14	CNRM	Aladin	25 km	ARPEGE	A1B
15	ICTP	RegCM	25 km	ECHAM5	A1B

RCM simulations have been proven to show systematic model errors (Ines and Hansen, 2006, Teutschbein and Seibert, 2012b). Therefore control runs tend not to agree with observed time series. For example, climate models simulate too many days with low intensity rainfall, making the RCM output to deviate from the observed rainfall (Ines and Hansen, 2006). To correct for these biases, two different approaches were used before driving PERSiST with the climate data. The first approach was to download an ensemble (Table 1) of RCM data corresponding to the studied catchments. Using multiple models covers a wider and more accurate range of uncertainties and the mean of these simulations may fall closer to observations. However, the chosen RCMs had a resolution (25 km) that greatly exceeded the size of the catchments. The solution was to averaging the temperature and precipitation values of the RCM grid cell with centre coordinates closest to the centre of the catchment and the values of its eight neighbouring grid cells.

The second approach was to correct for biases in the RCM outputs with a distribution mapping procedure where the cumulative distribution function (CDF) of the RCM-simulated climate data was adjusted to match the observed CDF. The distribution mapping procedure has been found to be the best correction method for small and meso-scale catchments in Sweden (Teutschbein and Seibert, 2012a). It is from here on described in three steps.

1. RCMs tend to simulate a large number of days with low precipitation when dry conditions are observed, so the first step was to introduce a precipitation threshold to avoid substantial distortion of the distribution.

2. Distribution parameters were calculated for both the observations and an RCM-simulated control run (1996–2008). Precipitation was fitted to a Gamma distribution and temperature was fitted to a Gaussian distribution. The simulated climate variable (precipitation or temperature) was then adjusted according to

$$C^{*}_{contr} = F^{-1}(F(C_{contr}|p_{1,contr}, p_{2,contr})|p_{1,obs}, p_{2,obs}) \quad (1)$$

where C is the climate variable and C^{*}_{contr} is the bias-corrected climate variable of the control run. F is the theoretical CDF (Gamma or Gaussian) and p_1 and p_2 are the distribution parameters for either the Gamma distribution or the Gaussian distribution.

3. The same distribution parameters ($p_{1,obs}$, $p_{2,obs}$, $p_{1,contr}$, $p_{2,contr}$) were then applied to adjust the climate variables of the RCM-simulated scenario run (2061-2090) according to

$$C^{*}_{scen} = F^{-1}(F(C_{scen}|p_{1,contr}, p_{2,contr})|p_{1,obs}, p_{2,obs}) \quad (2)$$

where C^{*}_{scen} is the bias corrected climate variable scenario run. This procedure is done with the underlying assumption that the biases are stationary in time, i.e. the same correction algorithm applies.

The bias corrected climate data (temperature and precipitation for 2061–2090) for each of the 15 RCM projections and for all four catchments were used in the hydrological projections. The bias corrected data contained 30 days for each month and included no leap years, which was not coherent with reality. This was fixed by running the data through a time adjusting software (not published) developed for INCA suite of models (Futter et al., 2007, Whitehead et al., 2011). Before driving PERSiST with the bias corrected and time adjusted future climate data, the data were used to analyse the expected future seasonal patterns in temperature and precipitation. These were estimated based on the average monthly temperature and the average monthly precipitation of all 15 RCM projections. The future seasonal patterns were assessed in contrast to the present day seasonal patterns.

2.3 PERSiST

2.3.1 Model Description

PERSiST; the Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport, is a catchment-scale hydrological model recently developed by Martyn Futter (Futter et al., 2013) at the Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences. One of the strengths of the model is that the model simulates runoff at one or more points in a river system. The model operates at a daily time step and is driven by daily series of air temperature and precipitation as well as other catchment characteristics. The model is simple to implement and builds on a series of first-difference equations fully described in (Futter et al., 2013).

PERSiST is extremely general when it comes to routing precipitation through the catchment. The water can be routed through an arbitrary number of buckets. For example, three buckets can be modelled to represent quick runoff, soil water and groundwater. Aside from the buckets, there is also a snow box for simulating the snow cover. There is a possibility to choose the number of landscape units to be modelled. For example, open mire and dry forest landscape within the same catchment do not have the same hydrological properties. It is therefore advantageous to be able to model them separately in PERSiST. There is also a possibility of modelling a catchment as separate subcatchments; with each of these subcatchments assigned their unique temperature and precipitation time series. This makes the conceptual model structure (Figure 2) fairly general to be applied to a wide range of environment. However, model conceptualization draws heavily on both the HBV (e.g. Andreasson et al., 2004) rainfall-runoff model and suite of Integrated Catchment model (INCA) (Futter et al., 2007, Oni et al., 2011, Whitehead et al., 2011.). PERSiST mimics the degree-day representation of snow dynamics and evapotranspiration found in HBV and utilizes the semi-distributed landscape framework used in INCA suite of models. However, flexible representation of terrestrial hydrology differentiates PERSiST from HBV (Futter et al., 2013).

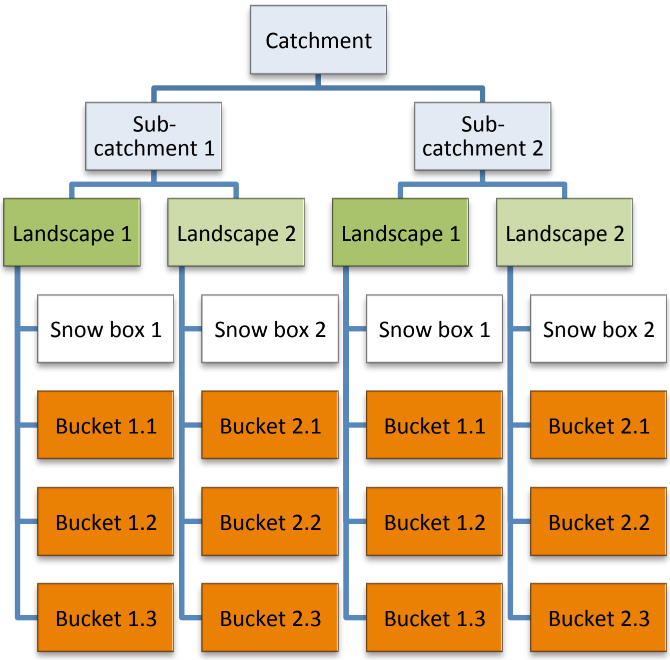

Figure 2. An example of a possible model structure using the PERSiST model

The degree-day representation of evapotranspiration incorporates a degree-day evapotranspiration parameter that defines the potential evapotranspiration that can occur when the temperature is above a growing degree-day threshold. No evapotranspiration is assumed when the temperature is below this threshold. The potential evapotranspiration can be described as

$$E(l) = l_1(T - l_2) \qquad (3)$$

where l_1 is the degree-day evapotranspiration parameter (mm°C^{-1}day^{-1}), T is the observed air temperature (°C) and l_2 is the growing degree-day threshold (°C). The actual evapotranspiration depends on the amount of moisture in each bucket.

The buckets are the water route from precipitation to streamflow (Figure 3). The design of a bucket decides the characteristics of the flow through the specific part of the terrestrial compartment that the bucket is chosen to represent. The depth of water (mm) draining from the bucket at time t can be described as

$$\Delta z_t = \frac{z_t - b_1}{b_2} \qquad (4)$$

where b_1 is the retained water depth (mm) and b_2 is a time constant (days) characteristic for the water draining at time t. With water depths below the retained water depth, water can no longer drain freely. The amount of water added to a bucket at a given time step cannot exceed the infiltration rate and the bucket cannot take more water than the max capacity. As long as the water depth in a bucket is above the retained water depth, the actual evapotranspiration will equal the potential evapotranspiration. When the depth of water is below the retained water depth, the actual evapotranspiration is slowed down and can be described as

$$E(b) = b_3 \left(\frac{b_1 - z}{b_1}\right)^{b_4} E(l) \qquad (5)$$

where b_3 is the relative evapotranspiration index and b_4 is an evapotranspiration adjustment.

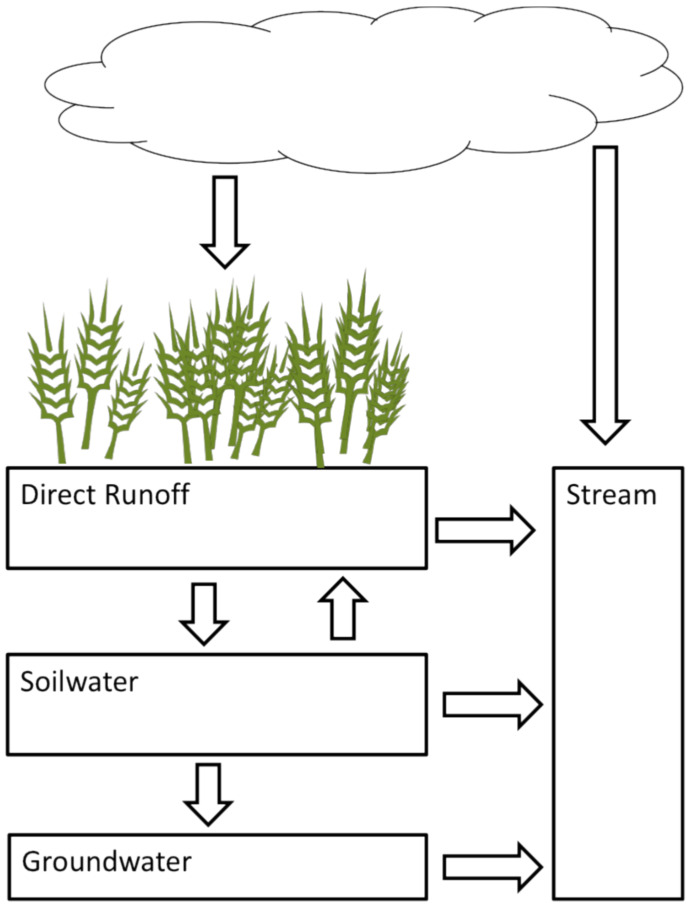

Figure 3. An example of interactions between three buckets (Direct Runoff, Soilwater and Groundwater) and the stream (Futter et al., 2013)

PERSiST uses a customizable square matrix in which the values help decide how the water flows into and out from the buckets and to the stream (Table 2), i.e. the interchange between the buckets as well as the exchange between the buckets and the stream (Figure 3). The values in Table 2 can all be set to a fraction between 0 and 1. For example, $m_{1,1}$ set to 0.5 would make 50% of the water in the quick runoff bucket flow directly to the stream. Furthermore, $m_{1,2}$ set to 0.5 would make the other 50% of the water in the quick runoff bucket flow to the soilwater bucket. In this example, $m_{1,3}$ (fraction of water in quick runoff bucket flowing into groundwater bucket) most be set to 0 because $m_{1,1} + m_{1,2} + m_{1,3}$ most always equal 1. The same approach is applied to all buckets (i.e. all rows in the matrix). The values on the main diagonal ($m_{1,1}$, $m_{2,2}$ and $m_{3,3}$) will always represent water flowing from the bucket to the stream.

Table 2. Square matrix in which the values help decide how the water flows in and out of the buckets and to the stream.

	Quick	Soilwater	Groundwater
Quick	$m_{1,1}$	$m_{1,2}$	$m_{1,3}$
Soilwater	$m_{2,1}$	$m_{2,2}$	$m_{2,3}$
Groundwater	$m_{3,1}$	$m_{3,2}$	$m_{3,3}$

Calculating the volume of water transferred from bucket i to bucket j the appropriate value in Table 2 ($m_{i,j}$) is multiplied by the depth of water draining from the bucket (Δz_t in Equation 4) and the relative bucket area (b_4).

$$V_{i,j} = m_{i,j}\, \Delta z_i\, b_4 \qquad (6)$$

The transferred volume $V_{i,j}$ is reduced if the empty volume in the receiving bucket (*j*) is smaller than the transferred volume from the source bucket (*i*). If the bucket is chosen to be a quick runoff bucket, then snowmelt and rainfall are added to $V_{i,j}$.

Buckets have the ability to simulate bidirectional flows during flooding where stream overflow its bank and inundates the surrounding areas or if there is infiltration from the stream to adjoining aquifers.

It is possible to specify parameters necessary to determine the flow velocity as a function of streamflow in each reach, as

$$v = aQ^b \qquad (7)$$

where v is the flow velocity (ms^{-1}), Q is the streamflow (m^3s^{-1}) and the multiplier a and exponent b are function parameters. Another advantage of PERSiST is the possibility to simulate anthropogenic inlets or outlets within the catchment, e.g. a drinking water uptake or an industrial outlet. Assigning a time series of water abstraction can simulate the removal of water from the streams. Assigning a time series of effluent can simulate the water addition to the streams.

The snow box is built on a simple degree-day-method, with the total daily snowmelt described as

$$M = C_M(T - T_b) \qquad (8)$$

where C_M is the degree-day-melt-factor, T is the daily mean temperature and T_b is the temperature where snowmelt first occurs, sometimes called the base temperature (USDA, 1972).

Running PERSiST requires three different files identified by their extensions; *.dat*, *.par* and *.obs*. The *.dat* file contains the temperature and precipitation data that drives the model. The *.par* file contains all the parameters that describe the model. It is also possible to modify the *.par* file by changing the parameter values in the model interface. The *.obs* file contains observed discharge for the simulation period for either calibrating or validating the internal working processes of the model.

After running a simulation, PERSiST is equipped with a user interface where charts showing simulated discharge, runoff, snow depth, input and output from each bucket etc. can be displayed. Observed discharge is plotted in the same chart as simulated discharge and different measurements of the goodness of fits are presented. The model goodness-of-fit is assessed using the Nash-Sutcliffe (NS) efficiency coefficient (Nash and Sutcliffe, 1970) that is widely used in hydrological modelling. The Nash-Sutcliffe model efficiency coefficient determines the predictive power of a hydrological model and is described as

$$NS = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \qquad (9)$$

where Q_o^t is the observed discharge at time t and Q_m^t is the modelled discharge at time t (Nash and Sutcliffe, 1970). The Nash-Sutcliffe value NS ranges from $-\infty$ to 1. If $NS = 1$ then the relationship between modelled discharge and observed discharge is a perfect match. If $NS = 0$ then the mean of the observed discharge is as good a prediction as the modelled discharge. If $NS < 0$ then the mean of the observed discharge is a better prediction than the modelled discharge. The Nash-Sutcliffe value is closely related to the coefficient of determination, denoted R^2.

2.3.2 Model Calibration

PERSiST was unable to validate against a non-continuous time series so the calibration was done for a period with continuous observed discharge data. Because of this the gaps of missing discharge data for Aneboda and Kindla catchments, limited data became an unwelcome restriction. Hydrology can have a great variability from year to year so it was important to calibrate the model for a sufficiently long time period. For each catchment the longest possible period was used using only full hydrological years (1^{st} October - 30^{th} September) (Table 3).

Table 3. Period of time that was used for calibration

	Period for calibration
Aneboda	1st October 2004 – 30th September 2008
Gårdsjön	1st October 1996 – 30th September 2008
Kindla	1st October 2004 – 30th September 2008
Krycklan	1st October 1996 – 30th September 2004

All four catchments were relatively small, ranging from 3.6 to 50 ha, so it was evident to model each catchment as a single reach without sub-catchments. The landscape was divided into two units; (1) *dry forest* and (2) *wet spruce and open mire*. Three buckets were used to represent *quick runoff*, *soil water* and *ground water* (Figure 4).

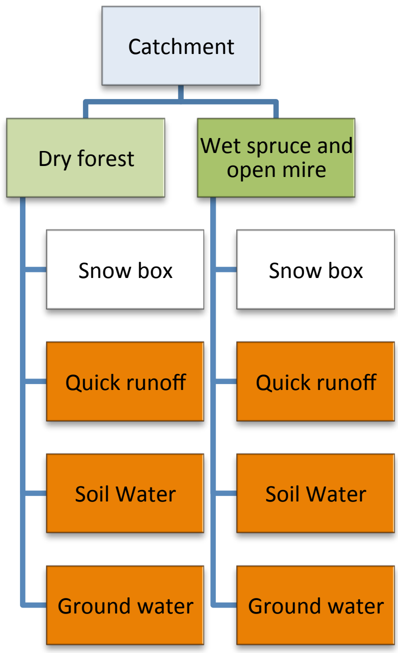

Figure 4. The model structure used when modelling the hydrology in the catchments Aneboda, Gårdsjön, Kindla and Krycklan

Calibration was done manually for one study site at a time. Both the temperature and precipitation series were put in *.dat* files while the observed discharge was put in *.obs* files. The *.par* files were modified individually for each catchment. The number of buckets was already set to three and landscape units set to two. The *.dat*, *.obs* and *.par* files were loaded into the model. The *.par* file was modified in the model interface to fit the study site but in a systematic way. First the known parameters, such as catchment area and landscape units were changed. Next, the parameters for the initial state were set. Since no heating up period was used it was important to set these parameters so to represent a reasonable initial state. These parameters include initial reach flow, initial snow depth and initial water depth in the buckets. The initial reach flow was set to a value identical to the observed discharge at the start date. Approximations were made for the initial snow depth and initial water depth in the model. Initial snow depth was set to zero since the hydrological year used started from 1st October. The water depth was initially set to simulate a wetter environment in the *wet spruce and open mire* than in the *dry forest*, i.e. a greater water depth in the *wet spruce and open mire* than in the *dry forest*. However, this did not hold for all sites if a greater water depth in the *dry forest* than in the *wet spruce and open mire* gave the best fit to observed discharge.

The square matrix was designed so as to best capture the dynamics of the discharge. Catchment characteristics such as bedrock outcrop and slope (difference in elevation) gave indications on how to design the square matrix. For example, a lot of bedrock outcrop and steep slopes indicated that a considerable amount of quick runoff would be routed directly to the stream. These catchment characteristics together with the catchment area also gave some hints on the residence time in each bucket. A provided parameter file for Simojoki in northern Finland (unpublished) gave some indications on reasonable evapotranspiration parameters that can be adapted to catchments on similar latitude. The model was run after every single change in any parameter to evaluate the effect of the change. Once the general dynamics of the discharge was found the goal was to find the set of parameters that gave the best possible Nash-Sutcliffe value, i.e. NS as close to 1 as possible.

Since the calibration period for some of the sites was so short it was considered better to use the whole available period for calibrating rather then divide it into a calibration and a validation part. This was to catch as much of the dynamics of the flow as possible.

2.3.2 Runoff Projection

To project the effect of future climate on stream discharge, the calibrated models for each catchment were run with the time adjusted and bias corrected RCM ensemble climate data (temperature and precipitation) from 2061 to 2089 hydrological year. It was assumed that the future catchments characteristics would have insignificant changes from what we have today. Therefore the same set of parameters and their values from calibration were used for future hydrological projections. This gave an ensemble of future stream discharge driven by different GCMs for Aneboda, Gårdsjön, Kindla and Krycklan.

2.3.2.1 Seasonal Change

To assess the change in the seasonal pattern for runoff, the projected monthly runoff was calculated for each of the simulations in the ensemble of future stream discharge. The average of projected monthly runoff for the whole ensemble was then assessed in contrast to the monthly runoff of the present day. In order to assess the contrast in all RCM ensembles, the projected monthly runoff maximum and minimum were considered as well.

2.3.2.2 Change in Precipitation-Runoff Patterns

To assess the change in precipitation-runoff patterns, the ensemble of projected precipitation and runoff were contrasted to the present day precipitation and runoff patterns. The precipitation-runoff relationships were assessed as annual precipitation and annual runoff for each catchment and for every RCM and not as an average of the ensemble. This made it possible to compare the individual RCM ensemble members to each other and to the present day conditions. To further elaborate on this point, the standard error of annual precipitation and runoff were calculated for every RCM projected and the present day series.

2.3.2.3 Changes along a Climatic Gradient

To assess the impact of climate change on runoff along a climate gradient of Sweden, Aneboda and Krycklan were set to represent the south-north gradient and Gårdsjön and Kindla was set to represent the west-east gradient. The future projections of annual runoff at the study sites were then compared to one another and to the present day conditions.

3. Results

3.1 Data Analysis

3.1.1 Historical Data

The mean annual temperature (Figure 5) and precipitation (Figure 6) showed that each study sites differed from each other in a climate perspective. This made the assessment of the impact of climate change along a climate gradient possible. The annual cycle of runoff (Figure 7) shows that the hydrologic regime changes along a south-north gradient. The further north the catchment is, the more extensive the snow cover during the winter. This has given rise to a hydrologic regime with more snow dominance and more pronounced spring flood towards the north. In the south of Sweden the runoff was instead more evenly distributed during the year but with more runoff during the winter than the summer. At Kindla there was a quite pronounced late summer peak in runoff. There was trace of this peak at Krycklan and Aneboda as well, although no trace of it at Gårdsjön.

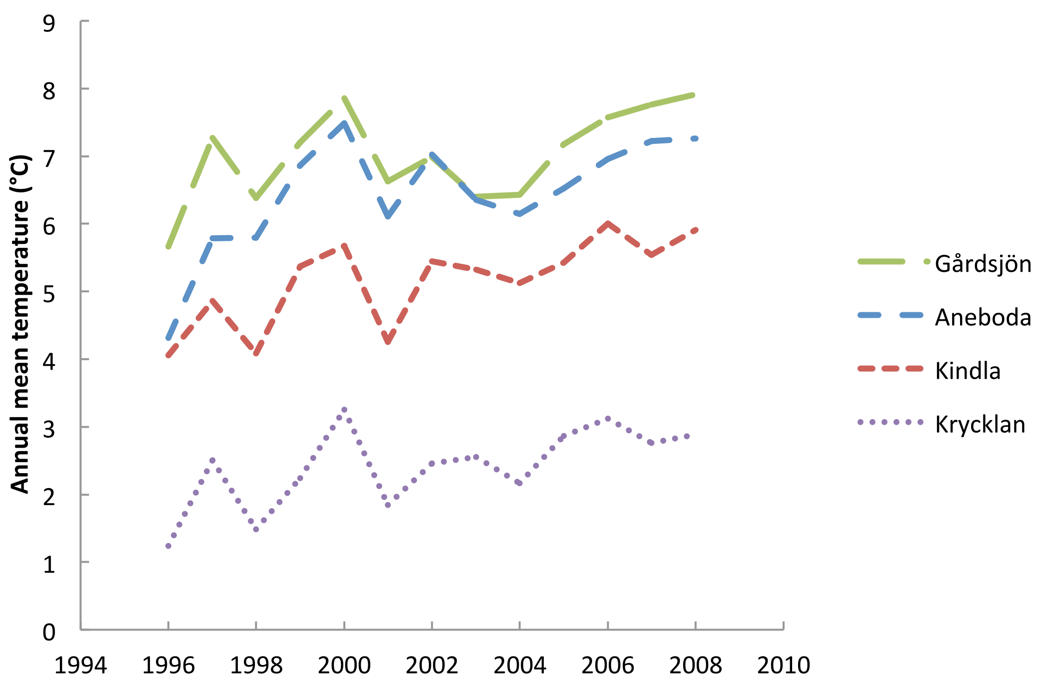

Figure 5. Mean annual temperature in all the study sites

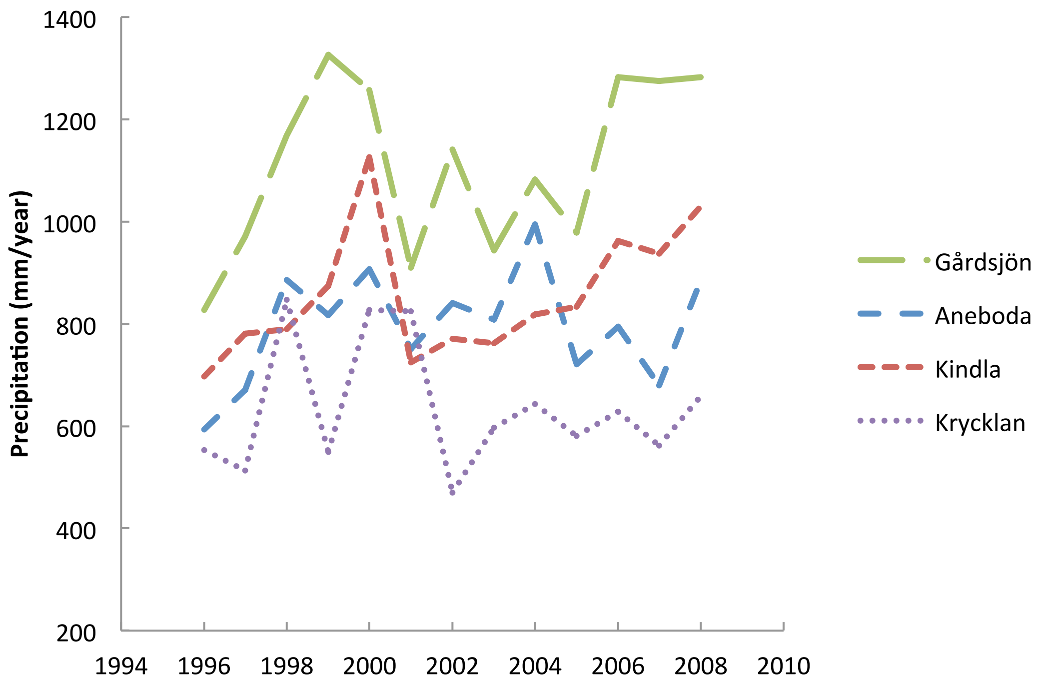

Figure 6. Mean annual precipitation in all the study sites

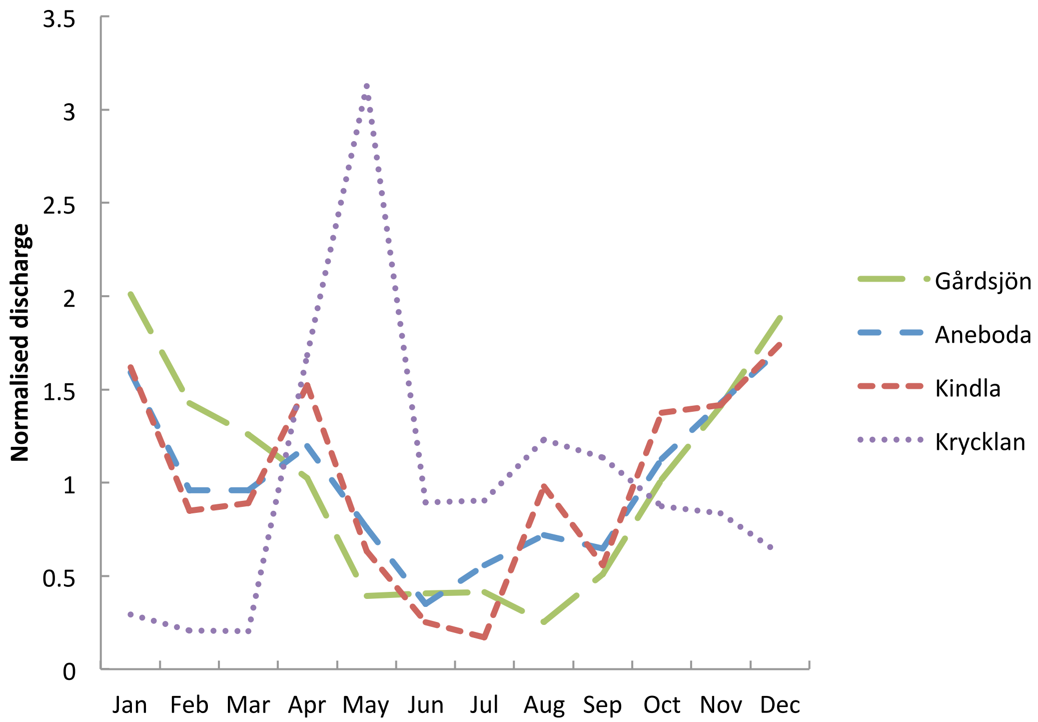

Figure 7. Normalisation of monthly discharge for each catchment for their respective calibration period (see Table 2)

3.1.2 Future Climate Data

The average projected annual cycle of temperature and precipitation for 2061-2090 (Figure 8 - Figure 11) showed that the temperature would increase significantly and the precipitation would increase more during the winter than during the summer. The period with temperatures below 0°C was projected to shorten considerably in the northern catchment (Krycklan) and to disappear completely in the southern catchments (Aneboda, Gårdsjön and Kindla). In Aneboda, the southernmost catchment, the precipitation would be almost unchanged compared to today during the late summer and autumn. The present day precipitation showed a peak in August at Gårdsjön. However, August at Gårdsjön was the only month with a projected clear decrease in monthly precipitation out of all sites. This leads to a slight loss of seasonality at Gårdsjön. Other than that, there was no evident total loss of seasonality in either temperature or precipitation at the other study sites.

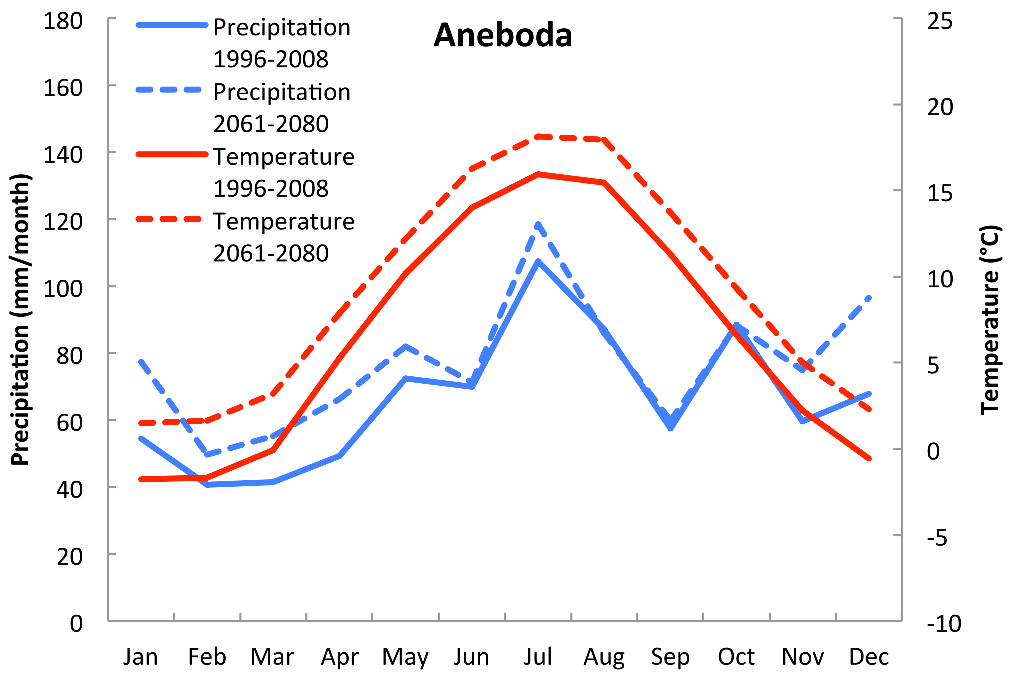

Figure 8. Monthly observed and projected temperature and precipitation in Aneboda catchment. Future projection represents the ensemble mean of the 15 RCMs (Table 1).

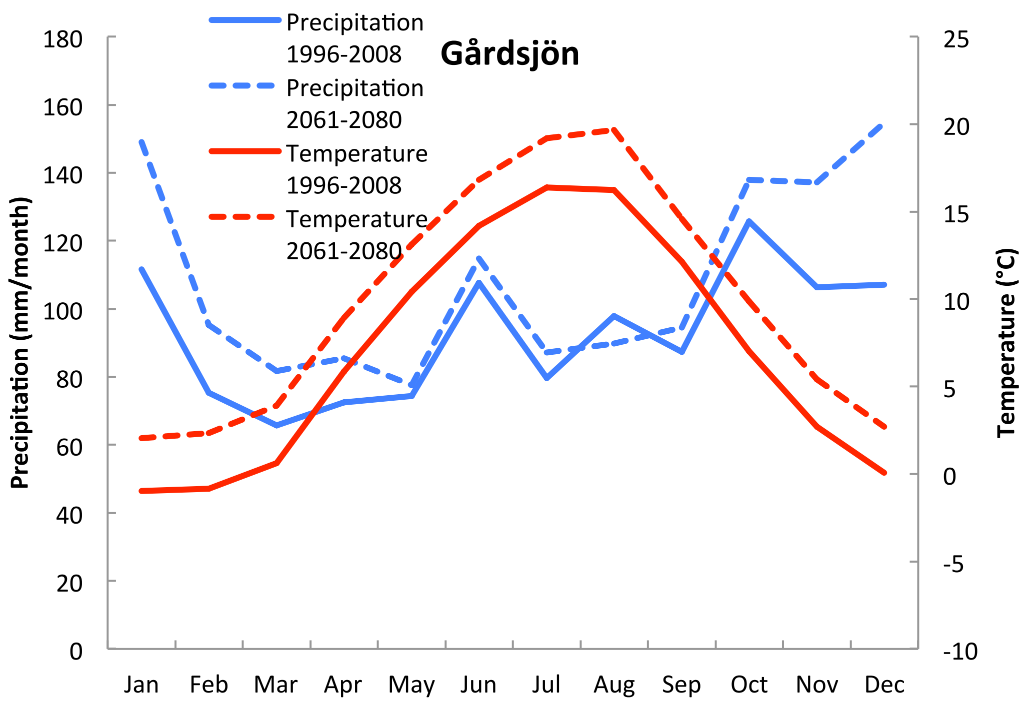

Figure 9. Monthly observed and projected temperature and precipitation in Gårdsjön catchment. Future projection represents the ensemble mean of the 15 RCMs (Table 1).

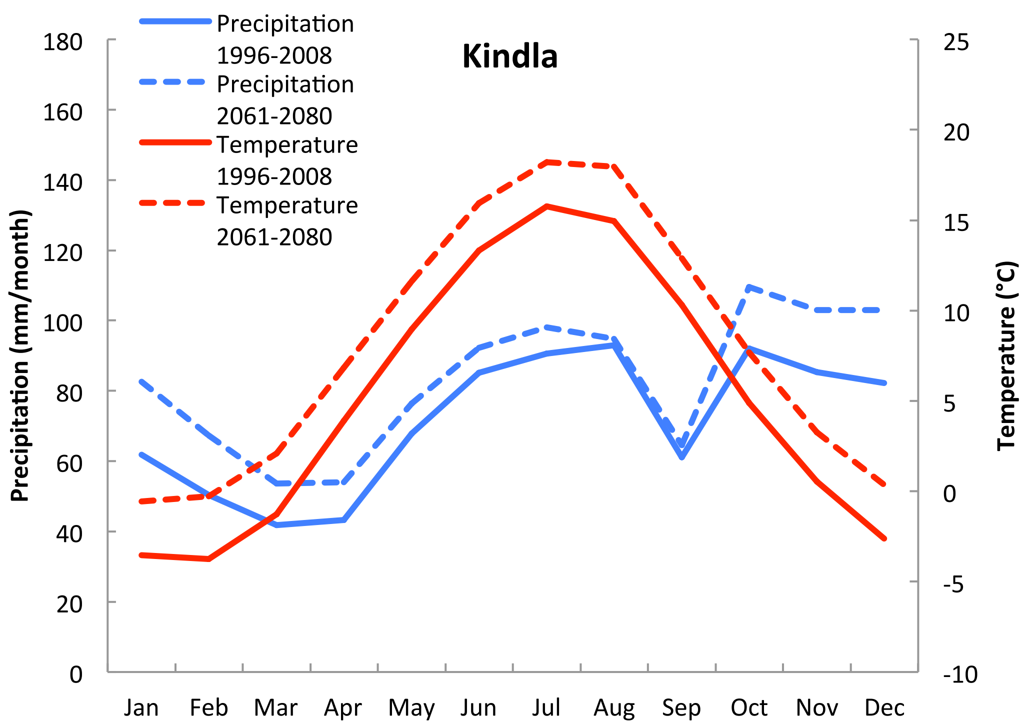

Figure 10. Monthly observed and projected temperature and precipitation in Kindla catchment. Future projection represents the ensemble mean of the 15 RCMs (Table 1).

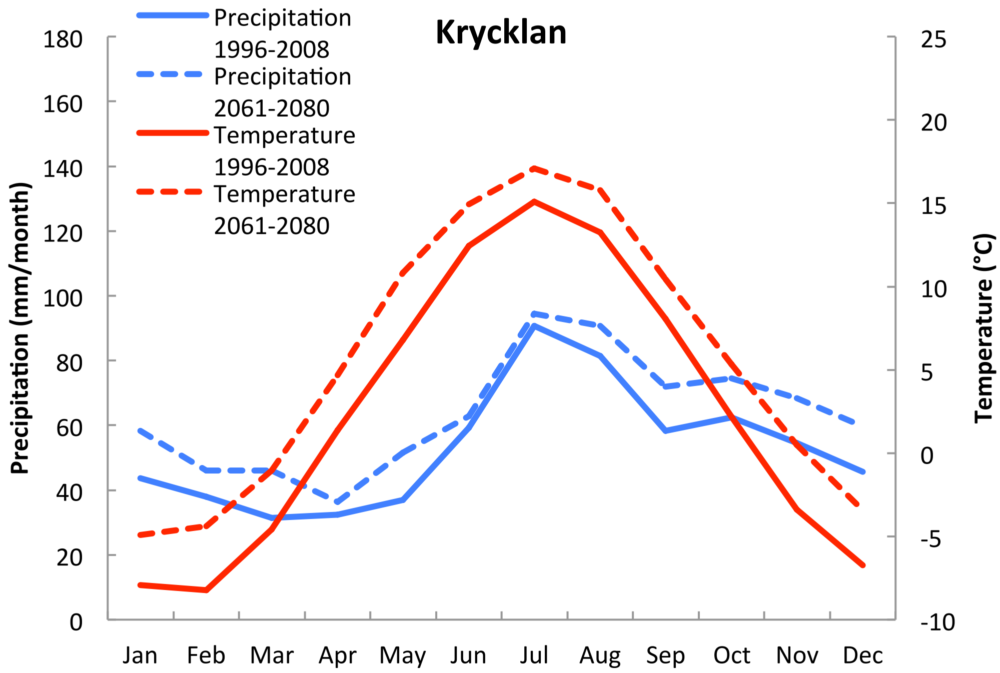

Figure 11. Monthly observed and projected temperature and precipitation in Krycklan catchment. Future projection represents the ensemble mean of the 15 RCMs (Table 1).

3.2 Model Calibration

The overall performance of the model was good. The model calibrated parameters; catchment parameters (Table 3), landscape parameters (Table 4) and square matrices (Table 5), gave simulated discharges that fit well with the observed discharges. Calibrating on all available data gave Nash-Sutcliffe 0.55 for Aneboda, 0.60 for Gårdsjön, 0.61 for Kindla and 0.76 for Krycklan catchment. The result of stream discharge for Anbeoda (Figure 12) showed an overestimated peak flow in the late summer of 2005 and an underestimated peak flow in the late autumn of 2006. The model also underestimated the baseflow throughout late summer to early winter in 2007. The results of stream discharge for Gårdsjön (Figure 13) showed that model underestimated the majority of the peak flows while the baseflow was better captured. The results of stream discharge for Kindla (Figure 14) showed that the model slightly underestimated the peak flows while the baseflow was captured in a better way but considerably overestimated discharge in the late summer of 2005. The results of stream discharge for Krycklan (Figure 15) showed a decent representation of the peak flows with the exception of an underestimated peak flow in the late summer/early autumn of 2001. The baseflow at Krycklan was well captured but the model had the tendency to overestimate the dynamics in the flow following a spring peak.

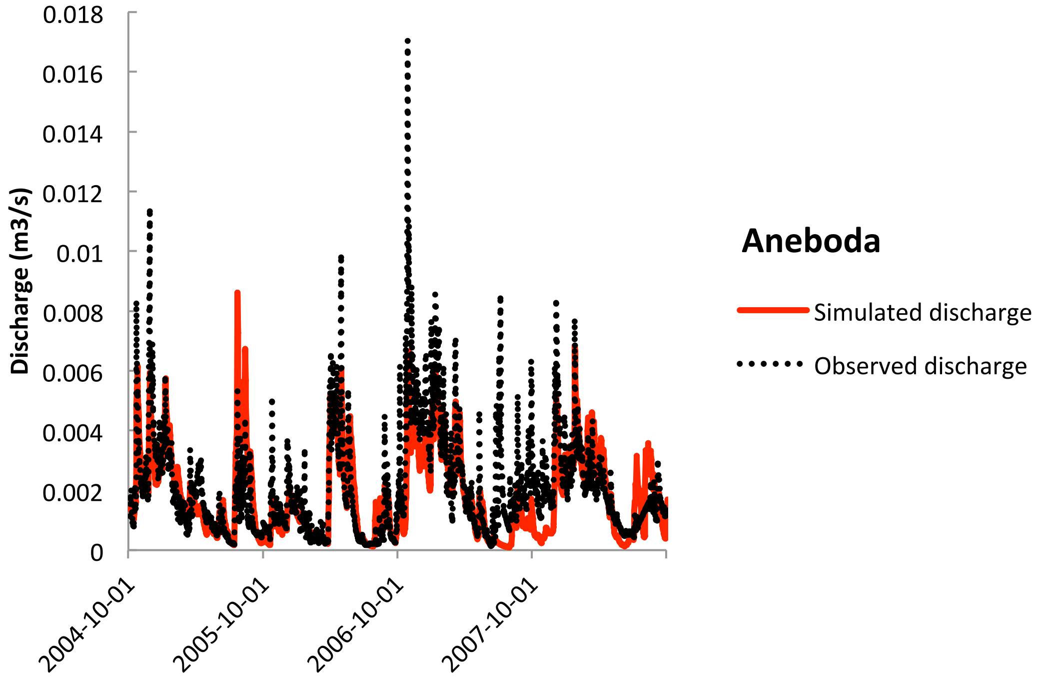

Figure 12. Aneboda simulated discharge and observed discharge for the calibration period (2004-2007, hydrological years)

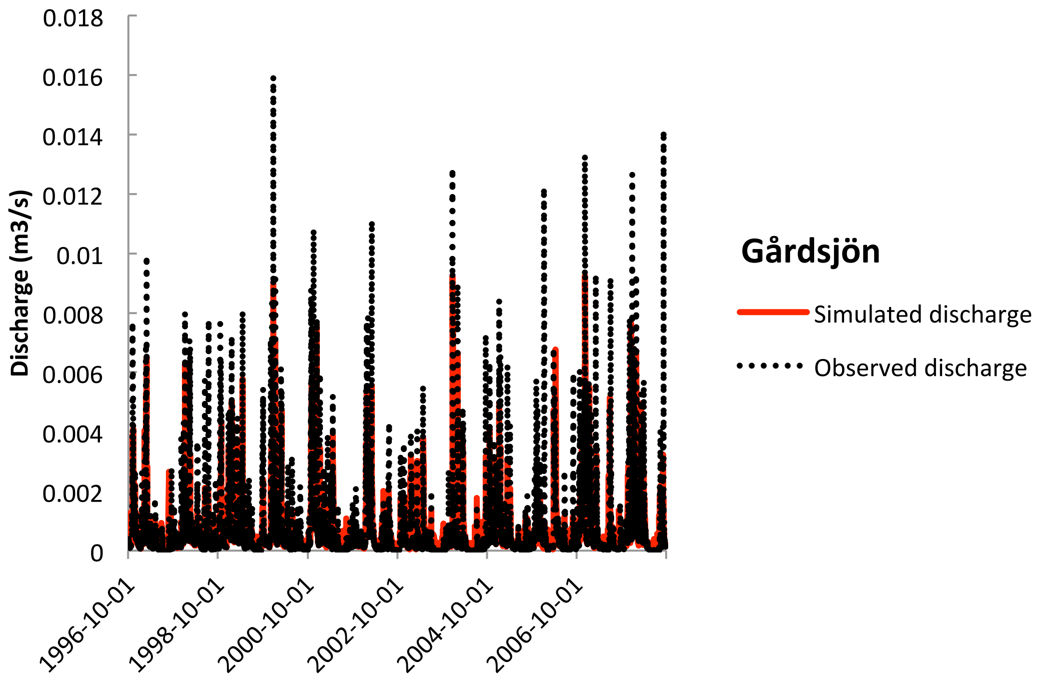

Figure 13. Gårdsjön simulated discharge and observed discharge for the calibration period (1996-2007, hydrological years)

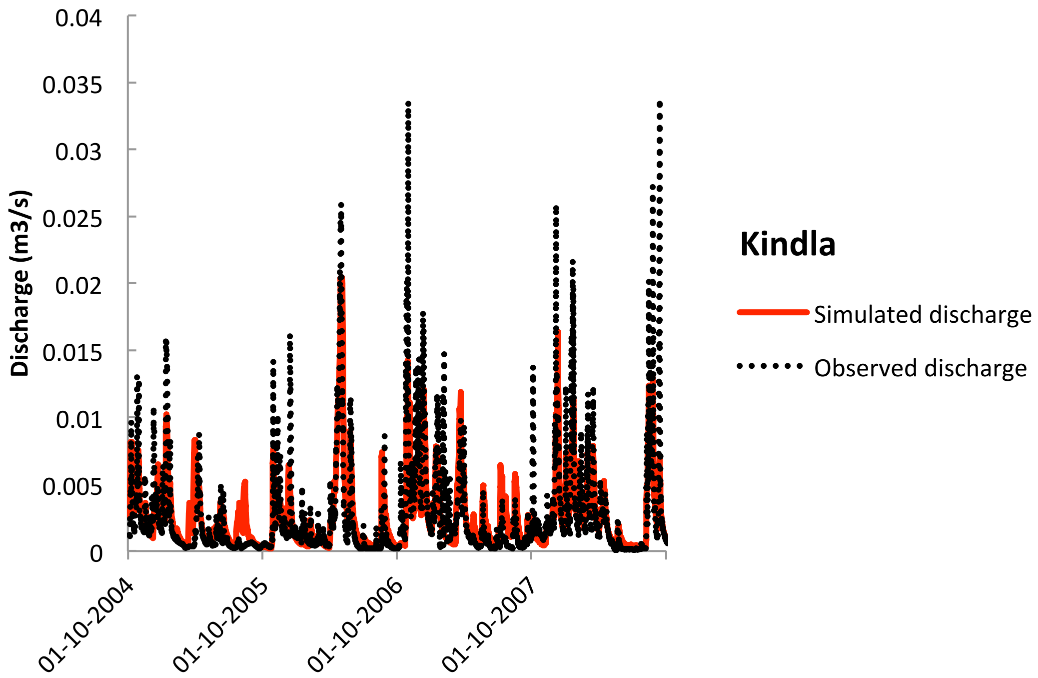

Figure 14. Kindla simulated discharge and observed discharge for the calibration period (2004-2007, hydrological years)

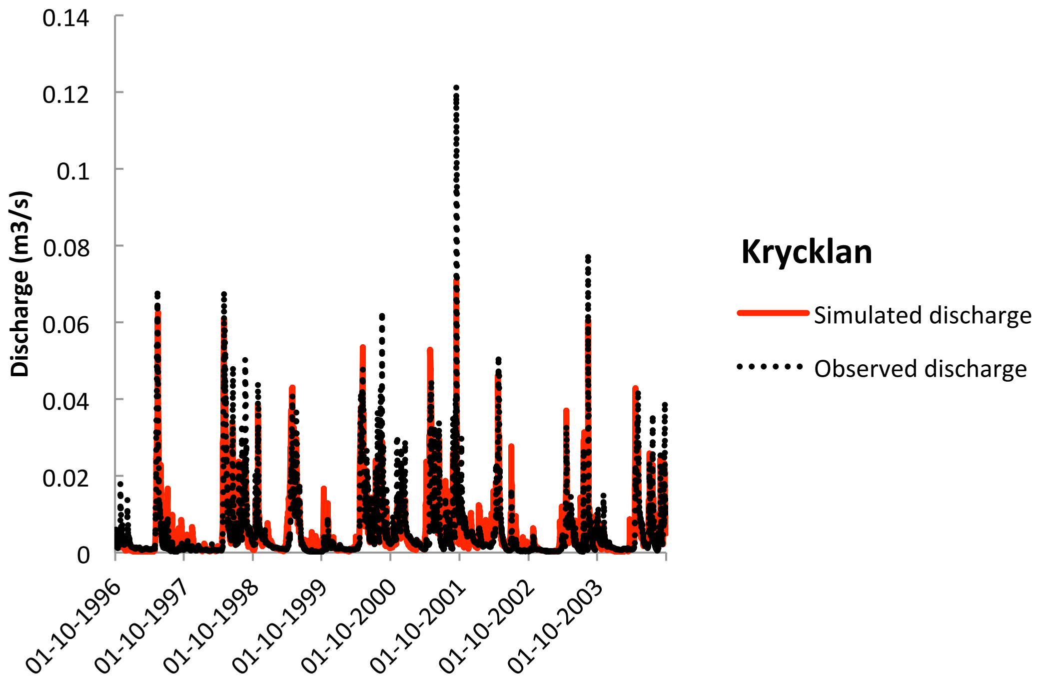

Figure 15. Krycklan simulated discharge and observed discharge for the calibration period (1996-2003, hydrological years)

Table 4. Catchment parameters for the study sites

Catchment parameters	Aneboda	Gårdsjön	Kindla	Krycklan
Catchment area (km^2)	0.189	0.037	0.204	0.50
Initial reach flow (m^3/s)	0.001	0.0001	0.001	0.0032
Abstraction (m^3/s)	0	0	0	0
Effluent (m^3/s)	0	0	0	0
Dry forest (%)	82	86	71	86
Wet spruce and open mire (%)	18	11	24	14

Table 5. Landscape parameters for the study sites

Landscape parameters	Aneboda		Gårdsjön		Kindla		Krycklan	
	Dry forest	*Wet spruce and open mire*	*Dry forest*	*Wet spruce and open mire*	*Dry forest*	*Wet spruce and open mire*	*Dry forest*	*Wet spruce and open mire*
Snow box								
Initial snow depth (mm)	0	0	0	0	0	0	0	0
Snow multiplier	1.1	1	1.1	1	1.1	1	1.1	1
Snow melt	1	3	2	4	1	2	2	4
Degree day melt factor (mm°C^{-1})	2	2	5	4	3	3	4	5
Rain multiplier	1	1	1	1	1	1	1	1
Degree day evapotranspiration (mm°C^{-1})	0.16	0.3	0.3	0.1	0.18	0.12	0.18	0.08
Growing degree threshold (°C)	0	0	0	0	0	0	0	0
Quick box								
Initial water depth (mm)	80	110	140	70	70	160	20	80
Relative area index	1	1	1	1	1	1	1	1
Infiltration (mm)	100	100	100	100	100	100	100	100
Retained water depth (mm)	110	130	90	90	70	100	200	50
Drought runoff fraction	0	0	0	0	0	0	0	0
Residence time (days)	2	2	1	1	2	1	1	1
Evapotranspiration adjustment	0	1.2	0	0	1	0	0	0
Relative evapotranspiration index	0	1	0	0	1	0	0	0
Max capacity (mm)	400	150	400	150	400	150	150	150
Inundation threshold (mm)	400	150	10	10	10	10	150	150
Porosity	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Soil water box								
Initial water depth (mm)	260	220	200	240	120	250	170	200
Relative area index	1	1	1	1	1	1	1	1
Infiltration (mm)	100	100	100	100	100	100	100	100
Retained water depth (mm)	250	210	230	260	150	250	200	220
Drought runoff fraction	0	0	0	0	0	0	0	0
Residence time (days)	35	6	2	1	14	13	20	3
Evapotranspiration adjustment	1	1	2	2	0.3	10	1	0.1
Relative evapotranspiration index	1	1	1	2	1	1	2	1
Max capacity (mm)	400	500	500	500	500	500	500	500
Inundation threshold (mm)	500	500	500	500	500	500	500	500
Porosity	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Ground water box								
Initial water depth (mm)	120	120	90	100	60	210	70	150
Relative area index	1	1	1	1	1	1	1	1
Infiltration (mm)	100	100	100	100	100	100	100	100
Retained water depth (mm)	100	100	110	100	100	100	150	150
Drought runoff fraction	0	0	0	0	0	0	0	0
Residence time (days)	40	40	1	1	100	30	200	2
Evapotranspiration adjustment	0	0	0	0	0	0	0	0
Relative evapotranspiration index	0	0	0	0	0	0	0	0
Max capacity (mm)	150	150	150	500	150	500	500	500
Inundation threshold (mm)	150	150	10	10	10	10	500	10
Porosity	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 6. Square matrix for each study site

Aneboda			
Dry forest			
	Quick	Soilwater	Groundwater
Quick	0.17	0.83	0
Soilwater	0	0.99	0.01
Groundwater	0	0	1
Wet spruce and open mire			
	Quick	Soilwater	Groundwater
Quick	0.5	0.5	0
Soilwater	0	0.9	0.1
Groundwater	0	0	1
Gårdsjön			
Dry forest			
	Quick	Soilwater	Groundwater
Quick	0.3	0.7	0
Soilwater	0	0.7	0.3
Groundwater	0	0	1
Wet spruce and open mire			
	Quick	Soilwater	Groundwater
Quick	0.1	0.9	0
Soilwater	0	0.9	0.1
Groundwater	0	0	1
Kindla			
Dry forest			
	Quick	Soilwater	Groundwater
Quick	0.6	0.4	0
Soilwater	0	0.1	0.9
Groundwater	0	0	1
Wet spruce and open mire			
	Quick	Soilwater	Groundwater
Quick	0.2	0.8	0
Soilwater	0	0.6	0.4
Groundwater	0	0	1
Krycklan			
Dry forest			
	Quick	Soilwater	Groundwater
Quick	0.2	0.8	0
Soilwater	0	0.7	0.3
Groundwater	0	0	1
Wet spruce and open mire			
	Quick	Soilwater	Groundwater
Quick	0.1	0.9	0
Soilwater	0	0.9	0.1
Groundwater	0	0	1

3.3 Runoff Projection

3.3.1 Seasonal Change

Running the climate data from the ensemble of RCMs through each calibrated model showed that there would be noticeable changes in the water regime in 2061-2089 compared to the present day runoff conditions (Figure 16 - Figure 19). All study sites showed that spring flood would be less dominant or even non-existent in Aneboda, Gårdsjön and Kindla. In the case of Krycklan, the peak spring flood could appear approximately one month earlier. In Aneboda, Gårdsjön and Kindla, there could be higher flows during the summer months and slight increase in winter. Stream flow in Krycklan would increase significantly in the winter due to the thinner and less constant snow cover, i.e. more melt periods.

In Aneboda, there was a wide variation in the ensemble projections. The seasonal patterns of runoff (Figure 16) showed highest runoff in the winter for both the observed and projected. The observed runoff was least in June, while the least runoff was projected in September. The spring flood was projected to decline to a state of non-existence of runoff peak. Although a trace of the spring flood could still be seen in the ensemble maximum. The ensemble minimum projected less runoff relative to the observed. The ensemble maximum projected more runoff relative to the observed, but less runoff in autumn. The ensemble maximum also showed a high increase in runoff during the summer months. The ensemble mean projected more runoff relative to the observed from late winter to early summer, but less in late summer, autumn and early winter. The ensemble mean and minimum showed a possibility of loss of seasonality in Aneboda as evident in their more evenly distributed runoff projections.

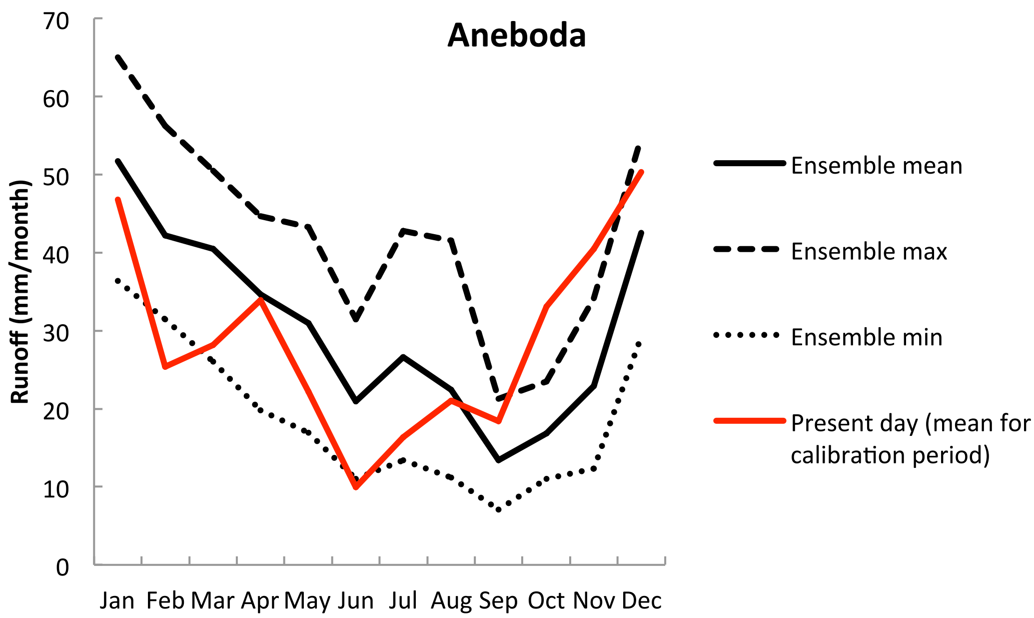

Figure 16. Projected runoff in Aneboda (2061-2089, hydrological years) compared to the observed present day runoff (2004-2007, hydrological years)

The seasonal pattern of runoff in Gårdsjön (Figure 17) showed highest runoff in the winter for both the observed and projected future condition. The observed runoff was least during the summer, and this was also true for the projected runoff. There was a trace of a spring flood in the observed runoff but the ensemble of projections showed no spring flood. However, the ensemble mean, minimum and maximum predicted a summer peak in June. Other than that, the observed runoff fell within a more narrow range of projected runoff compared to Aneboda (Figure 16) and Kindla (Figure 18). The ensemble maximum showed an increase in runoff in all seasons, while the ensemble minimum showed a decrease in runoff except summer where there is little to no change. The ensemble mean did not differ much from the observed runoff with the exception of an increase in runoff during the summer months. There was no clear loss of seasonality at Gårdsjön.

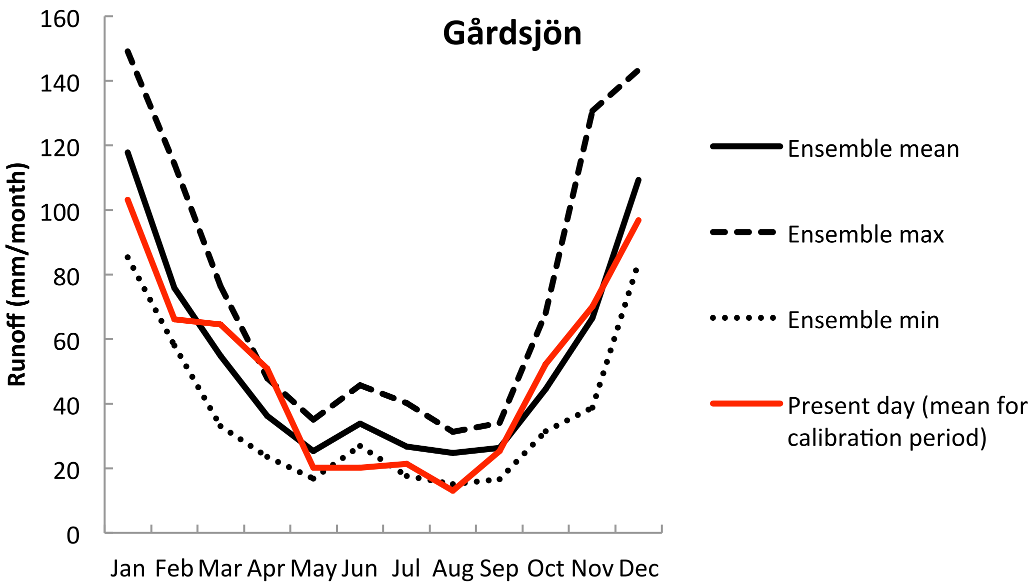

Figure 17. Projected runoff in Gårdsjön (2061-2089, hydrological years) compared to the observed present day runoff (1996-2007, hydrological years)

The seasonal patterns of runoff in Kindla (Figure 18) showed highest runoff during the winter for both the present day and future conditions. However, the observed runoff peaked in December through January and then decline in February. This was followed by a pronounced spring flood in April. However, the projected runoff showed high flows throughout the winter. In comparison to the observed runoff, the whole range of ensembles projections showed higher runoffs in June through July. The projected runoff then showed no peak in August, which was observed. The ensemble minimum projected less runoff on an annual scale while the ensemble maximum projected more runoff regimes. The ensemble maximum also showed some seasonality with high runoff in the winter (like Aneboda) and some increases in runoff during the summer. For the ensemble mean and minimum, the projected loss in runoff seasonality was very pronounced.

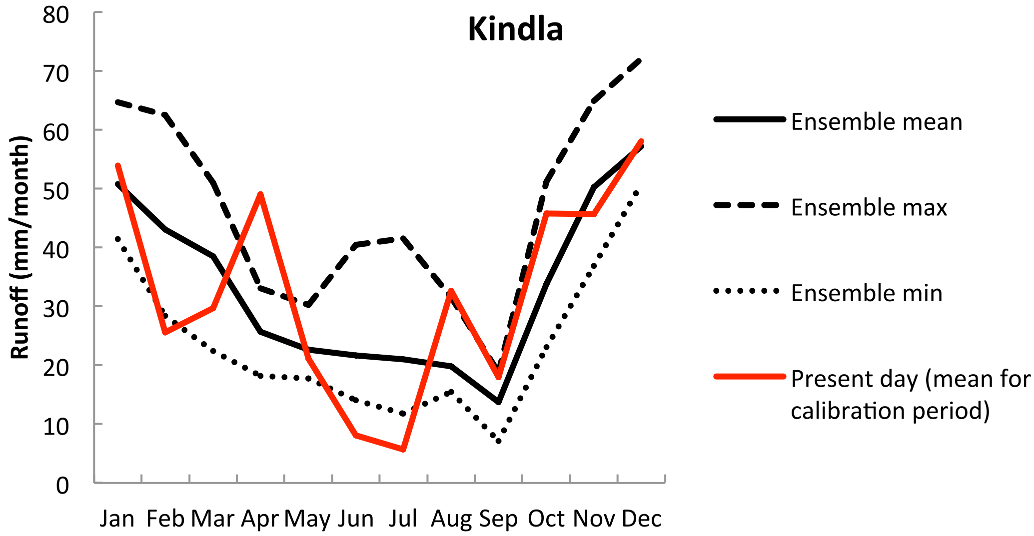

Figure 18. Projected runoff in Kindla (2061-2089, hydrological years) compared to the observed present day runoff (2004-2007, hydrological years)

The seasonal patterns of observed and projected runoffs in Krycklan (Figure 19) differed significantly from the other more southern catchments. The seasonal pattern of observed runoff showed a well-defined spring peak in May. However, all RCM projections showed the possibility of spring peak shifting to April. The ensemble mean projected a lower spring peak than observed, while the ensemble max predicted a slightly higher spring peak. The whole range of projections showed that runoff could increase during the winter months (January to March) preceding the spring flood. The observed runoff during the summer and autumn resembled the ensemble mean and fall within the range of future projections. Due to the increase in winter runoff and the lower spring peak (as shown by the ensemble mean and minimum), there could be some loss of well-defined runoff seasonality that characterised Krycklan.

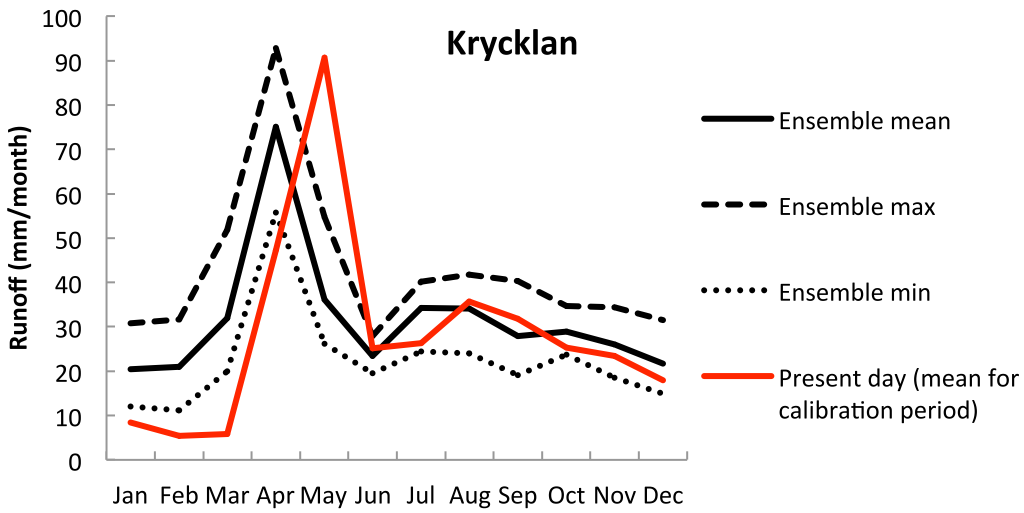

Figure 19. Projected runoff in Krycklan (2061-2089, hydrological years) compared to the observed present day runoff (1996-2003, hydrological years)

3.3.2 Change in Precipitation-Runoff Patterns

Relating the precipitation and runoff patterns in all future RCM ensemble projections in all study sites showed a general pattern: more precipitation and more runoff (Figure 20 - Figure 23). The present day conditions did not fall in the exact same pattern as the range of future projections. The projections suggested that it would take more precipitation to generate the same amount of runoff due to higher temperatures.

The overall precipitation-runoff patterns for the 15 RCM ensembles and the present day condition at Aneboda (Figure 20) showed that all RCMs projected an increase in annual precipitation. However, there were both an increase and decrease in annual runoff though more RCMs projected increase than decrease. RCM 2, 6, 8 and 14 made a close cluster of projections that significantly differ from the range projected by other RCMs. This cluster projected the driest future conditions at Aneboda while RCM 4 projected the wettest and most extreme precipitation and runoff conditions.

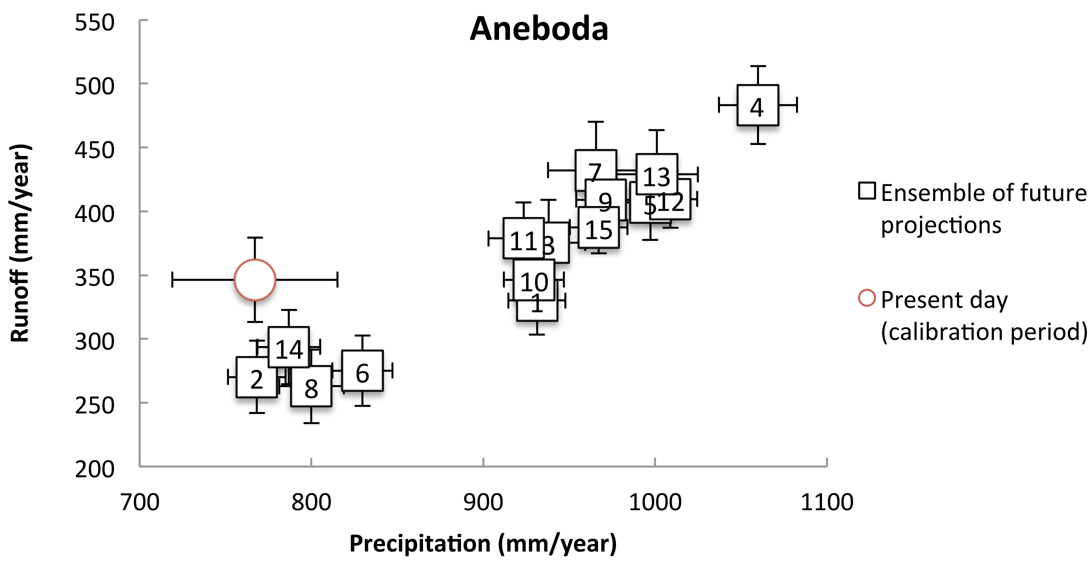

Figure 20. Projected annual precipitation and runoff (2061-2089, hydrological years) in Aneboda relative to the observed runoff (2004-2007, hydrological years) used for calibration. See Table 1 for the interpretation of RCM numbering sequence.

The precipitation-runoff patterns for the RCM ensemble and for the present day condition at Gårdsjön (Figure 21) showed that all RCMs except RCM 2 projected an increase in annual precipitation. Some RCMs projected increase and some decrease in annual runoff at Gårdsjön, with a majority of the RCMs projecting an increase. RCM 2 projected the driest conditions and RCM 5 projected the wettest and most extreme precipitation and runoff conditions. RCM 6 and 7 behaved strangely relative to others. For example, RCM 6 projected more runoff in contrast to other RCMs with the same amount of future precipitations. On the contrary, RCM 7 projected less runoff in contrast to other RCMs that projected the same amount of precipitation.

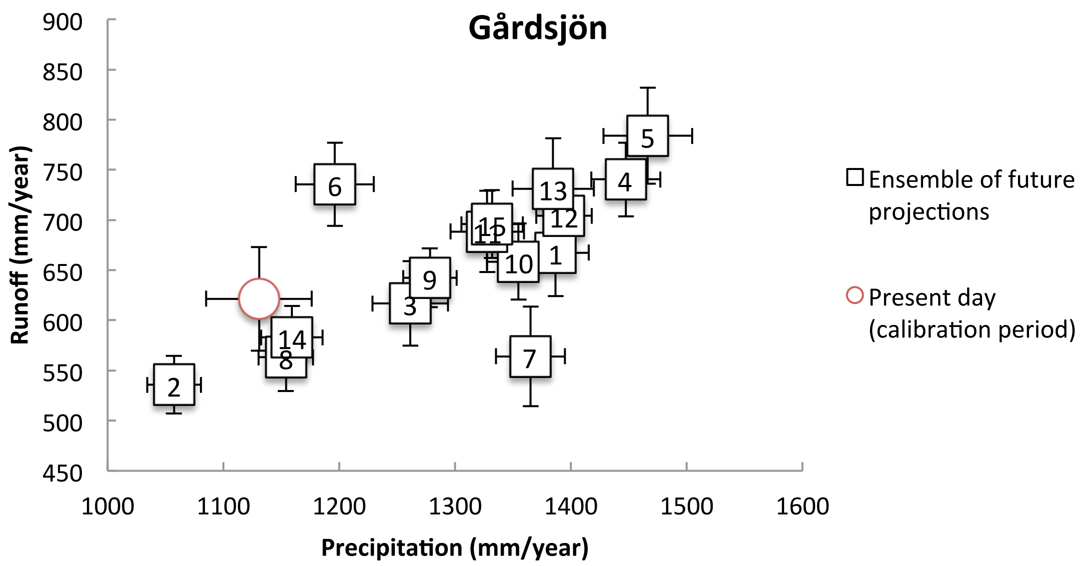

Figure 21. Projected annual precipitation and runoff (2061-2089, hydrological years) in Gårdsjön relative to the observed runoff (1996-2007, hydrological years) used for calibration. See Table 1 for the interpretation of RCM numbering sequence.

The precipitation-runoff patterns for the RCM ensemble and the present day conditions in Kindla (Figure 22) showed that all RCMs except 2 and 14 projected an increase in annual precipitation. Some RCMs also projected increase and some decrease in annual runoff but with majority towards increase. RCM 14 projected the driest condition at Kindla while RCM 13 projected the wettest and most extreme precipitation and runoff condition.

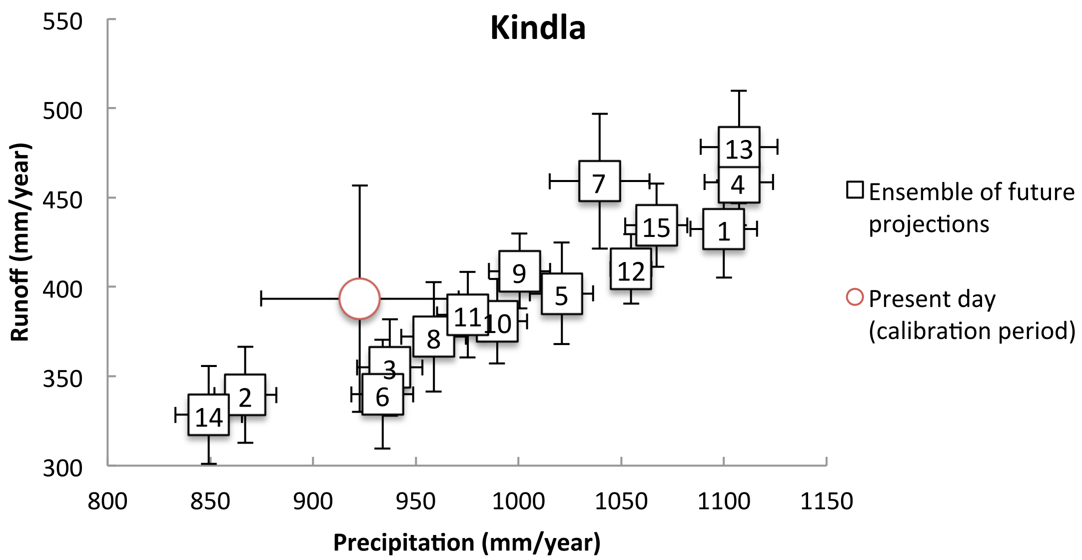

Figure 22. Projected annual precipitation and runoff (2061-2089, hydrological years) in Kindla relative to the observed runoff (2004-2007, hydrological years) used for calibration. See Table 1 for the interpretation of RCM numbering sequence.

The precipitation-runoff pattern for the ensemble projections and for the present day condition at Krycklan (Figure 23) showed that all RCMs except 2 projected an increase in annual precipitation. All RCMs except 2 and 14 also projected an increase in annual runoff. RCM 2 and 14 projected the driest future conditions and were found to lie outside the range projected by others. RCM 1 projected the highest annual precipitation but it was RCM 4 that projected the most annual runoff at Krycklan.

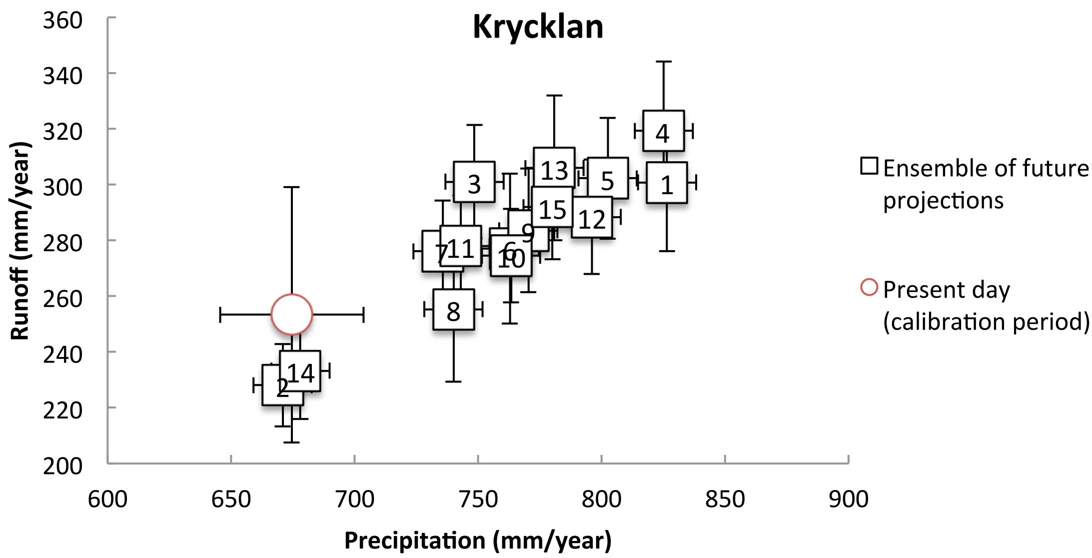

Figure 23. Projected annual precipitation and runoff (2061-2089, hydrological years) in Krycklan relative to the observed runoff (1996-2003, hydrological years) used for calibration. See Table 1 for the interpretation of RCM numbering sequence.

3.3.1 Changes along a Climatic Gradient

Exploring the change in runoff-precipitation patterns for all study sites (

Figure 24. Annual runoff-precipitation relation with standard error for all sites. Present day (red) as annual average of observed during calibration period and projection (black) as annual average of ensemble mean.) indicated a shift in a hydroclimatic gradient. Aneboda and Kindla catchments were projected to draw closer to each other in a hydroclimatic perspective. This is because of the significant increase in precipitation in Aneboda (+21%). Gårdsjön would also see a significant increase in precipitation (+15%) and further distinguish itself as the wettest catchment out of the four. Looking at the south-north gradient, the results showed a bigger increase in annual runoff in the north compared to the south. The present day annual runoff at Krycklan (north) during the calibration period was 253 mm/year and the projected annual runoff was 281 mm/year (+11%). The present day annual runoff at Aneboda (south) was 346 mm/year and the projected annual runoff was 366 mm/year (+6%). Both the percentage increase and the actual increase were bigger in the north. Looking at the west-east gradient, the results showed a great increase in annual runoff in the west and almost no increase at all in the east. The present day annual runoff at

Gårdsjön (west) was 621 mm/year and the projected annual runoff was 661 mm/year (+6%). The present day annual runoff at Kindla (east) was 393 mm/year and the projected annual runoff was 399 mm/year (+2%). Both the percentage increase and actual increase were bigger in the west.

The change in annual precipitation was +21% in Aneboda, +15% in Gårdsjön, +8% in Kindla and +13% in Krycklan. Despite the fact that Aneboda and Gårdsjön could have greater increase in annual precipitation, Krycklan was the site showing the greatest impact of climate change on annual runoff (+11%).

Assessing the magnitude of uncertainty in future projections along a climate gradient as standard error (error bars to black markers in

Figure 24. Annual runoff-precipitation relation with standard error for all sites. Present day (red) as annual average of observed during calibration period and projection (black) as annual average of ensemble mean.) showed that the uncertainty varies from catchment to catchment. The standard error of projected annual precipitation was 29 mm/year at Aneboda, 39 mm/year at Gårdsjön, 27 mm/year at Kindla and 21 mm/year at Krycklan. The standard error of projected annual runoff was 20 mm/year at Aneboda, 29 mm/year at Gårdsjön, 16 mm/year at Kindla and 13 mm/year at Krycklan. The standard errors for the present-day annual runoff and precipitation (error bars to red markers in

Figure 24. Annual runoff-precipitation relation with standard error for all sites. Present day (red) as annual average of observed during calibration period and projection (black) as annual average of ensemble mean.) are larger than the projected due to the way standard error was calculated and the short calibration period.

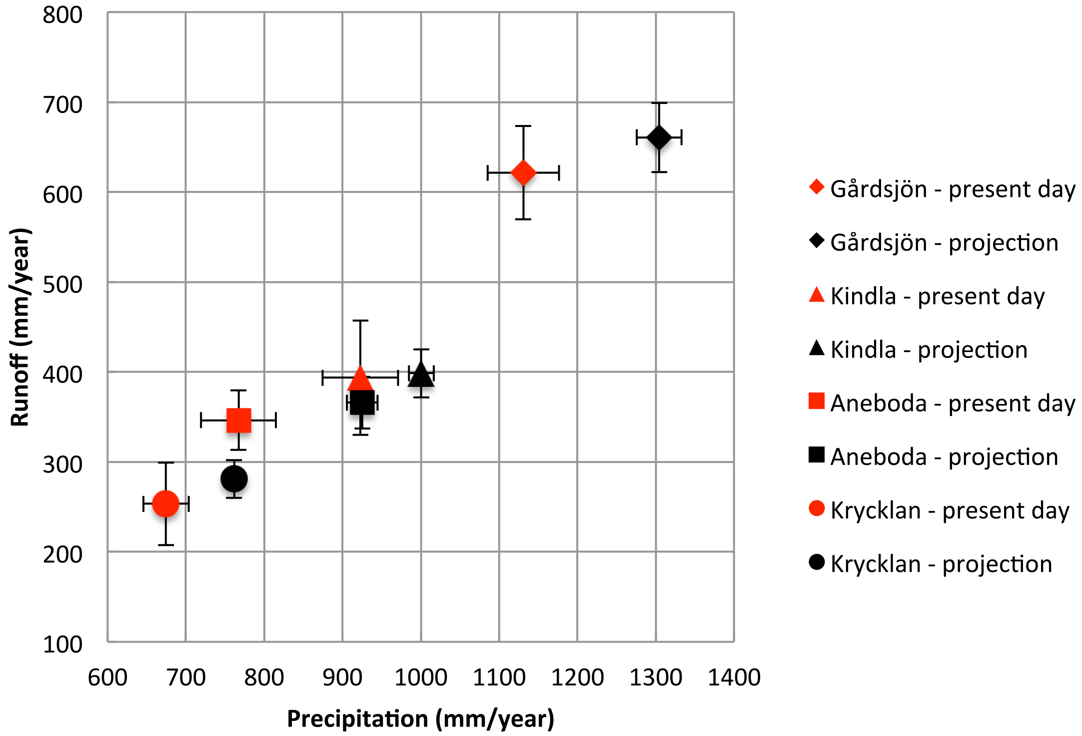

Figure 24. Annual runoff-precipitation relation with standard error for all sites. Present day (red) as annual average of observed during calibration period and projection (black) as annual average of ensemble mean.

4. Discussion

Assessing the impacts of climate change on runoff using PERSiST was important because the use of a new model gave further ground to the subject. The model PERSiST builds on a very general model structure that can be set up almost anyway you want it. This called for a lot of well-known catchment characteristics. In the case of the IM-sites many of the characteristics were known. However, when using the approach of simulating a model structure as close as possible to the real catchment, even more knowledge of the catchments' behaviour would have been beneficial. In spite of this, PERSiST did mainly good and most of the results agreed well with previous studies.

4.1 Model Calibration

The calibration gave a sufficient fit for all catchments but the peak flows were not always captured satisfactory. Also, the period of calibration for Aneboda and Kindla was too short. The hydrology of a catchment can show great variations from year to year. This makes it important to calibrate and validate hydrological models against a time series of proper length. This becomes even more important if the catchment is under external influences, such as forest managements, that change the hydrology momentarily. The IM-sites and Krycklan have been subject to a minimum of external influences but the storm Gudrun that hit Aneboda in January 2005 can be looked at as an inevitable external influence. Aneboda catchment was calibrated for the 1st October 2004 – 30th September 2008 period. During this time the storm can be considered to have had a momentarily impact on the hydrology, which could add to the uncertainty of the future projections. The fact that the model was used for simulating runoff under conditions that deviate from the calibration conditions, i.e. a different climate, can be considered an uncertainty in itself. The study sites had been assumed to have similar characteristics in 2061-2090 as they have today. However, this may not be true for some of the catchments.

A wider understanding and empirical knowledge of the studied catchments' runoff generating processes would probably have benefitted the manual calibration process. However, another approach that could have improved the calibration is using a Monte Carlo method. A Monte Carlo method may not give parameter values reflecting the actual runoff generating processes in the catchment but still yield a simulated streamflow fitting the observed. The case can be made that this is true for the manual calibration used in this study as well. However a Monte Carlo method could have been more appropriate to sample all parameter spaces for possible optimum values.

4.2 Future Projections

The wide range (depicted by ensemble maximum and minimum) of runoff projections showed the importance of using an ensemble of RCM for climate impact study. This somewhat constrains the uncertainty in future projections in comparison to the use of a single RCM or GCM. Despite the large uncertainties, this study has been worthwhile since it has utilized a new hydrological model and further assessed the plausible impacts of climate change on runoff.

4.2.1 Seasonal Change

The shift in the annual cycle of river flow, the result that the spring flood will be less dominant in the north and non-existing in the south, agreed well with previous studies done with the HBV-model (Bergström et al., 2001, Andréasson et al., 2004). However, the results differed from the earlier studies in one aspect; the projected hydrological condition through PERSiST showed that summer runoff could increase in southern Sweden while the earlier studies concluded that the summer runoff would decrease in southern Sweden. This probably has to do with the fact that the climate data used in the SMHI study predicts a decrease in precipitation for the summer months in southern Sweden. The climate data used in this study predicts a slight increase or no change in precipitation for the summer months at the south catchments, with the obvious exception of August at Gårdsjön where the precipitation decreases (Figure 9).

The decreasing spring floods projected in this study could be partly attributed to shortcomings of model calibrations during the spring events. Since the calibrated model simulates lower peak flows than observed, the decrease in spring floods might not be as pronounced as projected. However, earlier study conducted by SMHI (Andréasson et al., 2004, Bergström et al., 2001) came to the conclusion that spring floods could recede in the future. The shift in timing of the spring flood from May to April in Krycklan indicated a thinner snow cover that would melt faster. This shift in timing is in agreement with historical observation of advancement in other spring events, such as leaf unfolding (Menzel and Fabian, 1999) that can be attributed to the change in air temperature. Due to the increase in air temperature and less constant snow cover, an extended growing season length would be likely in the future.

4.2.2 Change in Precipitation-Runoff Patterns

The projected shift in precipitation-runoff pattern can be attributed to the increasing evapotranspiration. The future patterns indicate that it could take more precipitation to generate the same amount of runoff. This is due to the increasing air temperature, leading to higher evapotranspiration. An extended growing season might amplify this effect furthermore.

4.2.3 Changes along a Climatic Gradient

The results showed that the studied catchments differ in their level of response to climate change. There was no evidence of loss of seasonality in Gårdsjön. However, the loss was quite pronounced in Krycklan and Kindla that are located in the north. The impact of climate change has before been predicted to be larger in higher latitude catchments (Tetzlaff et al., 2013, Laudon et al., 2013). The northernmost catchment Krycklan showed the largest increase in annual runoff, a pronounced loss in seasonality and a shift in timing of the spring flood. These add up to strengthen the conclusion that Krycklan catchment could have the largest response to climate change.

The hydropower in Sweden is concentrated around the river networks in the north. Example of these is the Lule River with the highest energy production. The projected response (increase in runoff) in the north of Sweden will bring new conditions under which the hydropower production will operate and could be beneficial to the hydropower production. The increased winter runoff will provide an opportunity to produce more power during the winter, which is when the demand of electricity is the greatest. An increase in hydropower potential in Lule River due to climate change has been projected before (Graham et al., 2007).

5. Conclusions

Runoff for the years 2061-2080 was simulated using the PERSiST model, calibrated for the Aneboda, Gårdsjön, Kindla and Krycklan catchments. The model was driven by downscaled and bias-corrected future climate data for the study sites. The results indicated that the impact of climate change would differ along a south-north or east-west climatic gradient of Sweden. The spring flood that characterised Krycklan catchment in the north would most likely decline and appear one month earlier. The stream flow in Krycklan could also increase during the winter months due to less snow cover and as a result lead to loss of runoff seasonality. The loss of seasonality would not be pronounced in the southern catchments; Aneboda and Gårdsjön. The results showed that the overall increase in annual runoff could be largest in Krycklan and least in Kindla. These observations further establish the fact that the impact of climate change on future runoff would be largest in the northern catchment such as Krycklan.

References

Allen, M. R. & Ingram, W. J. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature,* 419, 224-232.

Andréasson, J., Bergström, S., Carlsson, B., Graham, L. P. & Lindström, G. 2004. Hydrological change-climate change impact simulations for Sweden. *AMBIO: A Journal of the Human Environment,* 33, 228-234.

Bergström, S., Carlsson, B., Gardelin, M., Lindstrom, G., Pettersson, A. & Rummukainen, M. 2001. Climate change impacts on runoff in Sweden-assessments by global climate models, dynamical downscaling and hydrological modelling. *Climate Research,* 16, 101-112.

Chou, C., Chiang, J. C., Lan, C.-W., Chung, C.-H., Liao, Y.-C. & Lee, C.-J. 2013. Increase in the range between wet and dry season precipitation. *Nature Geoscience*, 6, 263-267.

Crossman, J., Futter, M., Oni, S., Whitehead, P., Jin, L., Butterfield, D., Baulch, H. & Dillon, P. 2012. Impacts of climate change on hydrology and water quality: Future proofing management strategies in the Lake Simcoe watershed, Canada. *Journal of Great Lakes Research*, 39, 19-32.

Fowler, H., Blenkinsop, S. & Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology,* 27, 1547-1578.

Futter, M., Butterfield, D., Cosby, B., Dillon, P., Wade, A. & Whitehead, P. 2007. Modeling the mechanisms that control in−stream dissolved organic carbon dynamics in upland and forested catchments. *Water Resources Research,* 43(2), W02424, DOI: 10.1029/2006WR004960.

Futter, M., Löfgren, S., Köhler, S., Lundin, L., Moldan, F. & Bringmark, L. 2011. Simulating Dissolved Organic Carbon Dynamics at the Swedish Integrated Monitoring Sites with the Integrated Catchments Model for Carbon, INCA-C. *Ambio,* 40, 906-919.

Futter, M., Erlandsson, M., Butterfield, D., Whitehead, P., Oni, S. & Wade, A. 2013. PERSiST: The Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport. *Hydrology and Earth System Sciences Discussion*, 10, 8635-8681.

Graham, L. P., Andréasson, J. & Carlsson, B. 2007. Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods–a case study on the Lule River basin. *Climatic Change,* 81, 293-307.

Ines, A. V. & Hansen, J. W. 2006. Bias correction of daily GCM rainfall for crop simulation studies. *Agricultural and Forest Meteorology,* 138, 44-53.

Laudon, H., Tetzlaff, D., Soulsby, C., Carey, S., Seibert, J., Buttle, J., Shanley, J., Mcdonnell, J. J. & Mcguire, K. 2013. Change in winter climate will affect dissolved organic carbon and water fluxes in mid‐to‐high latitude catchments. *Hydrological Processes,* 27, 700-709.

Löfgren, S. 2002. *Integrerad övervakning av miljötillståndet i svensk skogsmark-IM: årsrapport 2008*, Institutionen för vatten och miljö, Sveriges lantbruksuniversitet, Uppsala. 34.

Löfgren, S., Aastrup, M., Bringmark, L., Hultberg, H., Lewin-Pihlblad, L., Lundin, L., Karlsson, G. P. & Thunholm, B. 2011. Recovery of soil water, groundwater, and streamwater from acidification at the Swedish Integrated Monitoring catchments. *Ambio,* 40, 836-856.

Mccabe, G. & Wolock, D. 1997. Climate change and the detection of trends in annual runoff. *Climate Research,* 8, 129-134.

Menzel, A. & Fabian, P. 1999. Growing season extended in Europe. *Nature,* 397, 659-659.

Murphy, J. M., Sexton, D. M., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M. & Stainforth, D. A. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature,* 430, 768-772.

Nash, J. & Sutcliffe, J. 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology,* 10, 282-290.

Oni, S., Futter, M. & Dillon, P. 2011. Landscape scale control of carbon budget of Lake Simcoe: A process based modelling approach. *Journal of Great Lake Research*, 37, 160-165.

Oni, S., Dillon, P., Metcalfe, R. & Futter, M. 2012a. Dynamic modelling of the impact of climate change and power flow management options using STELLA: application to the Steephill Falls Reservoir, Ontario, Canada. *Canadian Water Resources Journal,* 37, 125-148.

Oni, S., Futter, M., Molot, L. & Dillon, P. 2012b. Modelling the long term impact of climate change on the carbon budget of Lake Simcoe, Ontario using INCA-C. *Science of the Total Environment,* 414, 387-403.

Oni, S., Futter, M., Bishop, K., Kohler, S., Ottosson-Lofvenius, M. & Laudon, H. 2013. Long term patterns in dissolved organic carbon, major elements and trace metals in boreal headwater catchments: Trends, mechanisms and heterogeneity. *Biogeosciences*, 10, 2315-2330.

Solomon, S., Intergovernmental Panel On Climate Change. & Intergovernmental Panel On Climate Change. Working Group I. 2007. *Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge; New York, Cambridge University Press. 748-845.

Stehr, N. & Von Storch, H. 1994. *The social construct of climate and climate change*, Max-Planck-Institut für Meteorologie, Hamburg. 99-105.

Stewart, I. T., Cayan, D. R. & Dettinger, M. D. 2004. Changes in snowmelt runoff timing in western North America under a business as usual' climate change scenario. *Climatic Change,* 62, 217-232.

Tetzlaff, D., Soulsby, C., Buttle, J., Capell, R., Carey, S., Laudon, H., Mcdonnell, J., Mcguire, K., Seibert, S. & Shanley, J. 2013. Catchments on the cusp? Structural and functional change in northern ecohydrology. *Hydrological Processes*, 27, 766-774.

Teutschbein, C. & Seibert, J. 2012a. Is bias correction of Regional Climate Model (RCM) simulations possible for non-stationary conditions? *Hydrology and Earth System Sciences Discussions,* 9, 12765-12795.

Teutschbein, C. & Seibert, J. 2012b. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, 456-457, 12-29.

USDA, S. 1972. National Engineering Handbook, Section 4: Hydrology. *Washington, DC*.

Vedin, H., Raab, B., Wastenson, L. & Lantmäteriverket, S. 1995. *Sveriges nationalatlas: Klimat, sjöar och vattendrag*, Sveriges nationalatlas (SNA).

Whitehead, P., Jin, L., Baulch, H., Butterfield, D., Oni, S., Dillon, P., Futter, M., Wade, A., North, R. & O'connor, E. 2011. Modelling phosphorus dynamics in multi-branch river systems: A study of the Black River, Lake Simcoe, Ontario, Canada. *Science of the Total Environment,* 412, 315-323.

Winterdahl, M., Temnerud, J., Futter, M. N., Löfgren, S., Moldan, F. & Bishop, K. 2011. Riparian zone influence on stream water dissolved organic carbon concentrations at the Swedish Integrated Monitoring sites. Ambio, 40, 920-930.