UPPSALA
UNIVERSITET

UPTEC W 13039
Examensarbete 30 hp
November 2013

Clear-cut Effects on Snow Accumulation and Evapotransformation in a Boreal Catchment in Northern Sweden

Avverkningseffekter på snöackumulation och evapotranspiration i ett nordligt avrinningsområde

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Mikaela Rudling

Abstract

Clear-cut Effects on Snow Accumulation and Evapotranspiration in a Boreal Catchment in Northern Sweden

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The aim of this thesis was to investigate the processes behind an unexpected runoff behaviour after a clear-cut in a boreal forest in northern Sweden (Balsjö). The risks of increased flooding, erosion, nutrient leakage and changes in the local ecosystems are some reasons why it is important to fully understand the effect of clear-cuts on the water balance. In northern boreal forests the snow is of great importance as it results in the main hydrological event of the year, the spring flood. In general, open areas accumulate more snow, have a lower evapotranspiration and therefore maintain a higher runoff than a forest. In a recent paired catchment study at Balsjö the expected pattern after a clear-cut was only shown in three out of five years (2007-2011). The expected increase in runoff did not occur in 2010 and 2011. Two hypothesized alternatives were year-to-year variation of ET or changes in soil water storage.

In order to investigate this further the rainfall-runoff model HBV was used. First, the model was calibrated for the forest catchment (Ref) and the clear-cut catchment (CC), using observed data from Balsjö. To account for parameter uncertainty the calibration was performed using parameter optimization, resulting in 100 different parameter sets. Model results were evaluated using observed snow data from Balsjö and ET from Flakaliden, a nearby forest. Both the simulated snow and ET were quite consistent with the observed values. Finally the annual and the spring water balance were studied, using the simulated data.

The simulated results did not detect the unexpected runoff behavior for the two years as clearly as the observations. The reason for this was that the model was calibrated for all five years, which meant that annual variations were not taken into account. The hypothesis, that higher ET could be the reason for the unexpected runoff behavior, could neither be dismissed nor confirmed by this thesis. This was because there were no observed data for the clear-cut area and limitations within the HBV model, which meant that sublimation and interception processes could not be analyzed separately. The model results indicated that the change in soil water storage was a more likely explanation for the unexpected runoff behavior. The simulation result showed that the meltwater was stored in the soil water storage. However, this theory does not seem likely since a clear-cut is normally wetter than a forest.

The results of this thesis are consistent with other studies as they indicate that clear-cut effects should be studied seasonally as well as annually. The special feature of this thesis was the opportunity to study observed ET and investigate its influence on the water balance.

Key words: Clear-cut, HBV, boreal forest, runoff, evapotranspiration, snow accumulation

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Referat

Avverkningseffekter på snöackumulation och evapotranspiration i ett nordligt avrinningsområde i Sverige

Mikaela Rudling

Syftet med det här examensarbetet var att undersöka processerna bakom ett oväntat beteende hos avrinningen efter en avverkning i en boreal skog i norra Sverige (Balsjö). Riskerna med ökad översvämning, erosion, näringsläckage och förändringar i de lokala ekosystemen är några skäl till varför det är viktigt att till fullo förstå avverkningens effekter på vattenbalansen. I nordliga skogar har snön stor betydelse eftersom snösmältningen resultera i den största händelsen under det hydrologiska året, vårfloden. I allmänhet ackumulerar avverkade områden mer snö och har en lägre avdunstning än skogar. Därmed har de en högre avrinning än en skog. I en nyligen gjord parvisa avrinningsområdesstudie vid Balsjö, sågs det förväntade mönstret efter en avverkning bara i tre av fem år (2007-2011). Den förväntade ökningen av avrinningen visade sig inte för åren 2010 och 2011. Anledningen tros vara att evapotranspirationen (ET) varierar mellan åren, alternativt skillnader i markvattenlagring.

För att undersöka detta ytterligare användes avrinningsmodellen HBV. Först kalibrerades modellen för skogens avrinningsområde (Ref) och för avverkningsområdets avrinningsområde (CC) med hjälp av observerade data från Balsjö. HBV-modellens förmåga att simulera effekterna av en avverkning utvärderades med hjälp av observerade data av snömagasinets storlek från Balsjö och ET från Flakaliden, en skog i närheten. Både simulerade värden av snönmagasinet och ET överensstämde med de observerade värdena. Därefter undersöktes den årliga vattenbalansen samt vattenbalansen för vårsäsongen med hjälp av simulerade data.

De simulerade resultaten uppvisade inte det oväntade beteendet hos avrinningen för de två avvikande åren lika tydligt som för de observerade. Detta ansågs bero på att modellen kalibrerats för alla fem åren, vilket resulterade i att vissa årliga variationer missades. Hypotesen, att höga ET värden i avverkningsområdet kan vara orsaken till det oväntade beteendet hos avrinning kunde varken bekräftas eller avfärdas. Detta berodde på att det inte fanns observerad data för avverkningsområdet och begränsningar i HBV-modellen, därmed kunde inte sublimering och interception analyseras. Modellresultaten pekade på att skillnader i markvattenlagringen var en mer trolig förklaring till det oväntade beteendet hos avrinningen för 2010. Simuleringen visade att smältvatten lagrades i marken. Dock är denna teori inte troligt eftersom det är normalt sett är fuktigare i ett avverkat område än i en skog.

Resultaten från det här examensarbetet överensstämmer med andra studier som visat att avverkningseffekter bör studeras både årsvis och säsongsvis. Det speciella med den här studien var möjligheten att studera observerade ET och att undersöka dess inverkan på vattenbalansen.

Nyckelord: avverkning, HBV, avrinning, evapotranspiration, snöackumulering

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Preface

This thesis is the examining part of the *Master's Program in Environmental and Water Engineering* at Uppsala University. This thesis was initiated by Kevin Bishop, professor at Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University, who also has been the subject reviewer. The supervisor was Reinert Huseby Karlsen, PhD student at Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University.

First and foremost I would like to express my gratitude to my supervisor Reinert Huseby Karlsen who has been tremendously helpful in terms of guidance and support in the working process.
Furthermore I would also like to thank Kevin Bishop for initiating this thesis and for guidance it in the right direction.
I would also like to thank Jan Seibert, visiting professor at Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University for advice on the HBV model and also for helping with the writing process.
Further I would like to thank Allan Rodhe, professor at Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University who was the examiner for this thesis and whose knowledge of hydrology has been most helpful.

Finally I would like to show my appreciation to Jacob Schelker et al. (2013) for making such an interesting study which enabled this thesis and for letting me share their results and data. I would also like to thank Mikaell Ottosson Löfvenius, Senior Lecturer at Department of Forest Ecology and Management at the Swedish University of Agricultural Sciences who made the evapotranspiration data from Flakaliden available.

Uppsala, September 2013

Mikaela Rudling

UPTEC-W 13022 ISSN 1401-5765
Published digitally at the Department of Earth Sciences, Uppsala University, Uppsala, 2013.

Populärvetenskaplig sammanfattning

Avverkningseffekter på snöackumulation och evapotranspiration i ett nordligt avrinningsområde

Mikaela Rudling

Avverkningseffekter på vattenbalansen har studerats ända sedan medeltiden men frågor som hur avrinning, snöackumulation och avdunstning ändras efter en avverkning är fortfarande obesvarade. Risker som ökade översvämningar, erosion, näringsläckage och förändringar i de lokala ekosystemen är några av de problem som omger kalhyggen.

Vattenbalansen beskriver sambandet mellan nederbörd, avdunstning, avrinning och markvattenlagringen. I nordliga svenska skogar har snön stor betydelse eftersom dess snösmältning resulterar i det hydrologiska årets största händelse, vårfloden. Processer som styr snöackumulation är nederbörd, vind, lufttemperatur och strålning. Temperaturen och strålningen anses vara de processer som huvudsakligen styr snöackumulationen genom fyra mekanismer. Dessa mekanismer är interception, sublimering, avdunstning och transpiration. Interception är när nederbörd fångas upp av träden och därefter avdunstar från bladen. Sublimering är när snön förvandlas direkt till vattenånga och lämnar snötäcket eller snön i trädkronorna. Avdunstning är vatten som lämnar jorden, en vattenyta eller smältvatten till atmosfären i form av gas. Transpiration är det vatten som växterna tar upp via rötterna och sedan avges till atmosfären genom klyvöppningarna. Evapotranspiration (ET) är summan av avdunstning, sublimation och transpiration.

I allmänhet har avverkade områden mer ackumulerad snö och en lägre avdunstning och därmed en högre avrinning än ett skogsområde. Avverkade områden får också ofta en högre och tidigare flödestopp på våren. Ett vanligt sätt att undersöka avverkningseffekter är genom en parvisa avrinningsområdesstudie där två liknande och närliggande avrinningsområden studeras. Det ena avrinningsområdet är en orörd skog och används som en referens och det andra området är där avverkningen har utförts. Med denna metod kan effekterna av en avverkning studeras utan att skillnader i t.ex. nederbörd, vegetation och temperatur påverkar. I en nyligen gjord parvis avrinningsområdesstudie av en nordlig skog (Balsjö, försöksplats i norra Sverige) sågs det förväntade mönstret efter en avverkning enbart i tre av de fem studerade åren (2007-2011). Den förväntade ökningen hos avrinningen i avverkningsområdet observerades inte för 2010 och 2011. Anledningen tros vara att ET variera mellan åren, eller skillnader i markvattenlagring.

Syftet med det här examensarbetet var att undersöka vad det oväntade beteendet hos avrinningen kan bero på. Det gjordes genom att först kalibrera avrinningsmodellen HBV efter referensområdet (Ref) och avverkningsområdet (CC) i Balsjö. För att minimera parameterosäkerheter i modellen gjordes en parameteroptimering. HBV-modellens förmåga att simulera effekterna utvärderades med hjälp av observerade data av ackumulerad snö från Balsjö och ET från Flakaliden, en skog i närheten. Både det simulerade snömagasinet och ETn överensstämde med de observerade värdena även om de simulerade värdena tenderade att vara något underskattade. Likformigheten mellan simulerade och observerade värden var förvånande då HBV-modellen inte har särskilda parametrar som reglerar mekanismerna interception, sublimering och evapotranspiration. Detta korrigeras i modellen genom att vara inbyggt i snö- och markvattenlagringsparametrarna.

Den årliga vattenbalansen samt vattenbalansen för vårsäsongen analyserades med hjälp av simulerade data. De simulerade resultaten uppvisade inte det oväntade beteendet hos avrinningen för de två avvikande åren lika tydligt som de observerade. Detta ansågs bero på att modellen kalibrerades för alla fem åren, vilket resulterade i att vissa årliga variationer missades. Att höga ET värden under våren kunde vara orsaken till det oväntade beteendet hos avrinningen kunde varken avfärdas eller bekräftas. Detta berodde på att det inte fanns observerad data för avverkningsområdet och att HBV-modellen inte simulera ET under snösmältning, vilket innebär att processerna sublimering och interception inte kunde analyseras. Modellresultaten pekade dock på att hypotesen borde avvisas då den simulerade ETn för avverkningsområdet var lägre än för skogen under vårdperioden. I stället visade simuleringsresultatet att förändringen i markvattenlagringen var en mer trolig förklaring till det oväntade beteendet hos avrinningen för 2010. Detta berodde på att simuleringen visade att smältvatten lagrades i marken i avverkningsområdet, då skillnaden i markvattenlagringen var positiv i avverkningsområdet och negativ i skogen. Detta kan förklaras med att det snarare är ET under hösten och vintern som påverkar avrinningen i form av minskad markvattenlagring i avverkningsområdet. Dock verkar den teorin inte troligt eftersom det är normalt sett fuktigare i ett avverkat område än i en skog.

En korrelationsanalys gjordes där samband mellan effekten av en avverkning och observerade klimatparametrar studerades. Effekten presenterades som skillnaden mellan simulerad avrinning för de två avrinningsområdena Ref och CC. Klimatparametrarna utgjordes av observerad nederbörd och ET. Den årsvisa korrelationen visade att högre nederbörd resulterade i lägre avverkningseffekt och att högre ET ledde till högre avverkningseffekt. För vårssäsongen kunde inget samband påvisas, tvärtemot uppvisade vissa år ett beteende vilket var det raka motsatta till den årsvisa motsvarigheten.

Resultaten från detta examensarbete överensstämmer med andra studier som visar att avverkningseffekter så som ökad snöackumulation och avrinning liksom minskad ET är troliga. Även förslaget att avverkningseffekter bör studeras säsongsvis liksom årsvis förstärks i denna rapport då tydliga skillnader i simulerade värden mellan hela året och vårsäsongen kunde ses. Det speciella med denna studie var möjligheten att studera observerad ET för att undersöka dess inverkan på vattenbalansen, då det är kostsamt och omständigt att mäta. Dock uppvisade varken den observerade eller simulerade ETn under våren någon förklaring till det oväntade beteendet år 2010. En fördjupad säsongsstudie skulle kunna klarlägga huruvida tidigarelagd ET (höst och vinter) påverkar vårfloden i form av förändringar i marklagring eller huruvida sublimering och interception under snösmältningen påverkar avrinningen.

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List of abbreviations

CC	Clear-cut area, which stands for the catchment where the clear-cut were made.
ET	Evapotranspiration, which represents the actual water vapour from evaporation and transpiration.
ETsnow	Represents the evapotranspiration taking place during snow cover in the catchments. The main processes are sublimation and interception from the snowpack and the canopy.
PET	Potential evapotranspiration, which represents the theoretical calculated value of evapotranspiration from an unlimited water source.
Ref	Reference area, which stands for the catchment with an untreated forest.
SWE	Snow water equivalent, which represents the amount of water the snowpack represents, measured in millimetres.
SWEss	Represents the snowpack at the end of March and is the *start* value for the water balance for the *spring* period.
ΔSG	The change in groundwater storage presented as a sum of the two groundwater boxes in the HBV model representing the upper and the lower storage.
ΔSM	The change in soil water storage for the soil box in the HBV model.

For model parameters for the HBV model see Table 3

1. Introduction

The question of how the forest and water balance are linked were already raised in the Middle Ages in France after seeing wells dry out after massive clear-cutting (Andreassian, 2004). Today with overhanging risk of an unavoidable climate change and the increasing risks of inundation, leaching of nutrients and contaminations as well as vital changes of ecosystems, (Sørensen et al., 2009; Rosen et al., 1996) the understanding of the impact of deforestation seems more important than ever.

Since the Middle Ages several studies across the world have been performed on the subject, e.g. of the forest's impact on the water balance. The majority of the studies reached the same conclusion that after deforestation the runoff increases before decreasing again along with regrowth (Rosen et al., 1996; Seibert et al., 2010; Ide et al., 2013; Schelker et al., 2013). However the role of deforestation is not well quantified and many questions remain unanswered. The magnitude of the increased runoff differs between different studies. In studies made in Sweden the runoff, during the first years after the deforestation, varied from 20 to 270mm, which corresponds to an increase of 3% and 110% respectively (Sørensen et al., 2009). Studies on the effects of a clear-cut in boreal regions are but a few. In the recent study, *Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland,* by Ide et al. (2013) the result indicates long lasting effects after clear-cut, when looking at the different seasons rather than at the annual differences. Ide et al. observed that the annual effects diminished after eight years, while the spring flow continued to have the same increase in runoff as the years directly after the clear-cut. The difference in runoff before and after the clear-cut was measured and called treatment effect. Ide et al. saw that while the spring treatment effect remained positive during the study period the summer and autumn treatment effect changed from positive to negative after about eight years leaving the total annual treatment effect on a decreasing trend.

The change in winter and spring hydrology after deforestation depends on several processes such as snow accumulation, snowmelt, stream response (runoff) and sublimation (Schelker et al., 2010). In Swedish conditions, with forests of high-latitude, the increase of runoff after the deforestation is a result of mainly two things, a higher snow accumulation and a reduced evapotranspiration (Sørensen et al., 2009). How a greater snow accumulation in a clear-cut reflects in the runoff is still unclear, but an earlier snowmelt often results in changes in the magnitude and timing of peakflows, e.g. the peaktiming can vary from a few days to weeks compared to the forest area (Andréassian, 2004). The main processes behind different snow accumulation are changes in interception and the subsequent sublimation that typically result in lower accumulation in the forest than in a clear-cut area. Wind conditions have a larger impact on the clear-cut and result in a lower accumulation of snow because of increased evaporation and snow drift. (Schelker et al., 2010; Murray and Buttle, 2003). Furthermore, a clear-cut is more exposed to short-wave radiation and turbulent fluxes, which enhances the rates of snowmelt (Murray and Buttle, 2003; Schelker et al., 2013). How big effect the deforestation has is influenced by the extent of the catchment and the size and location of the deforestation area. In larger forest areas where a clear-cut only represents 1-10% of the total catchment area, the effects on peak flows are not of great importance compared to extreme weather conditions (Rosen et al., 1996; Brandt et al., 1988; Schelker et al., 2013). However, for a small catchment (<1 km^2) were the clear-cut often represents over 50% of the catchment area, the consequences can be substantial (Seibert and McDonnell, 2010).

One way to investigate the effects of land use change is the paired catchment approach (Seibert et al., 2010; Andréassian, 2004, Sørensen et al., 2009), where an untreated catchment works as a reference area compared to another catchment which is subjected to treatment. The method requires that the two catchments are similar when it comes to climate, precipitation, soil and geology, topography and vegetation. This means that the method can only be used for small catchments since the precipitation has a spatial variation for larger catchments (Seibert et al., 2010; Sørensen et al., 2009). An alternative would be to use a rainfall-runoff model like the HBV model (Hydrologiska Byråns Vattenavdelning), which can be used on larger catchments with no need of reference areas (Seibert et al., 2010; Seibert and McDonnell, 2010; Zerge, 2011). The HBV model is well known and used in similar research on the effects on runoff after a clear-cut (Brandt et al., 1988).

Another recent paired catchment study performed for the years 2006-2011 in Balsjö, a boreal forest in northern Sweden, by Schelker et al. (2013) shows an increase in snow accumulation for the following five years after a clear-cut. However, the corresponding increase in total volume of the spring flood could only be detected in three out of the five years (2007, 2008 and 2009). For the years 2010 and 2011 there were no significant differences in runoff between the reference area and the clear-cut area. The reason for the behaviour in Balsjö is believed to be the impact of sublimation and evapotranspiration (ET) or changes in the soil water storage between the two catchments. The question was therefore if the annual variation of ET can have the same magnitude of impact on the spring runoff as deforestation? The role of ET has not yet been fully investigated mainly because of the difficulties and costs of measuring ET. The idea for this thesis was to take observed ET data from Flakaliden, an area close to Balsjö, and evaluate the simulated ET (from the rainfall-runoff model HBV) for Balsjö to get a better insight of ET’s impact on the runoff. When measuring evapotranspiration all the water vapor leaving the area is measured. This means that there is no difference between water vapor from sublimation from the snowpack or from the intercepted snow in the canopy or evaporation and transpiration. During the spring and under the snowmelt the measured ET mostly represents sublimation and evaporation from the snowpack or from the canopy (ETsnow). The other possible explanation for the variation in the runoff behaviour in Balsjö was that the melt-water was stored in the soil instead of leaving as vapour to the atmosphere. Therefore the simulated soil water storage in the HBV model was also analysed.

The aim of this study was to investigate the effects a clear-cut had on snow accumulation, evapotranspiration and soil-storage in a boreal forest (Balsjö) using the HBV model with focus on the annual and spring period. The following research questions were asked

- After a clear-cut, do the snow accumulation and runoff increase and ET decrease?
- Do the simulated results show the same as the observed values from the Balsjö study by Schelker et al. (2013), does the unexpected runoff behaviour appear?
- How well does the HBV model manage to simulate changes in snow and ET after a clear-cut?
- Can variations of ET (ETsnow) or change in soil storage explain the unexpected behaviour in the runoff at Balsjö in 2010?
- Is there any relation between clear-cut effects and climate parameters such as precipitation and ET in Balsjö?

2. Materials and Methods

In order to answer the research questions the following method was used. The HBV model was calibrated describing two catchments, the reference area (Ref) and the clear-cut area (CC), using observed data of precipitation, temperature and discharge from the paired catchment study at Balsjö and potential evapotranspiration (PET) from Svartberget. To account for parameter uncertainty the calibration was performed using parameter optimization, resulting in 100 different parameter sets and 100 different simulations. An alternative model approach was first started but later dismissed since the approach required some modifications of the HBV model that did not fall within this study. The alternative approach is described in Appendix 1.

In order to evaluate the capacity of the HBV model to simulate the effects of a clear-cut, observed data were used. The observed data consisted of discharge and snow from Balsjö and ET from Flakaliden and were compared with the simulated values. The investigated years were 2009 and 2010 since they were believed to be years with an expected and unexpected runoff behaviour, respectively.

To see if there were any differences in the runoff behaviour between seasons, the annual and the spring water balances were studied by using the simulated data. The unexpected runoff behaviour was investigated by analysing simulated values with observed values for both the annual and the spring period.

In order to see if there was any relationship between the clear-cut effects in Balsjö and the climate parameters, precipitation and ET, a relation analysis were made. The clear-cut effects were expressed as the difference in simulated runoff between Ref and CC at Balsjö.

In this thesis mean values were used in all presentations and comparisons. This might seem strange since it is well known that most of the measured data of for example runoff are not normally distributed. The reason why mean values were used was that for some of the variables mean values were the only form available for the observed data. Another reason was that the HBV model uses mean values for the input variables (precipitation, temperature and discharge). In order to maintain continuity mean values were therefore used throughout the thesis.

2.1. Study sites

The data used in this thesis came from three different sites in the same area in northern Sweden. All sites are located about 60 km west of Umeå in Västerbotten (Table 1). The hydrological year is defined as 1st of October to 30th of September by the Swedish Meteorological and Hydrological Institute (SMHI) and the snow cover stays from November until May (Schelker et al., 2013). The snowmelt period (spring in this thesis) is defined as 1st of April until 31th of May since the peak runoff occurred during that time interval for the years (2004-2011) studied in Balsjö (Schelker et al., 2013). The three sites have similar vegetation and are classified as boreal forests, however some of them have parts that consist of mire, Table 1. The vegetation of the three sites comprises of Scots pine (Pinus sylvestris), in the higher well drained areas, and Norway spruce (Picea abies) in the lower moister areas. As undergrowth there are dwarf shrubs and cowberry (Empetrum sp.). Birch (Betula sp.) grows in the wetlands and forbs, sedges and grasses covers represent the ground vegetation. On the riparian zones there are different moss species (e.g. Sphagnum sp., Polytricum sp.) (Schelker et al., 2013; Sørensen et al., 2009; Bishop, 1991; Erefur, 2013). The difference and similarities of for example temperature, precipitation and soil properties, between the sites are presented in Table 1.

Table 1. A summary of the study sites Balsjö (Schelker et al., 2013; Sørensen et al., 2009; Löfgren et al., 2009), Svartberget (Bishop, 1991, Haei et al., 2010; Erefur, 2013) and Flakaliden (Lindroth, 2004). The annual runoff for Balsjön is calculated as mean values of the years 2006-2010 (Schelker et al., 2013b)

	Units	**Balsjö**		**Svartberget**	**Flakaliden**
Coordinates	-	64°02’N;18°57’E		64°14’N;10°46’E	64°14' N;19°46' E
Area	ha	CC (CC-4) 40.5	Ref (NR-7) 24.2	50	-
Meters above sea level	m	265-297		235-310 (225 climate station)	225
Annual temperature	°C	0.6		1.7	1.9
Annual precipitation	mm	554		612	587
Annual runoff	mm	CC 470	Ref 346	323	-
Dominant vegetation		Scots pine, Norway spruce		Scots pine, Norway spruce	Scots pine, Norway spruce
Soil texture	-	glacial till (orthic podsols)		glacial till (iron podzols)	sandy-silty till
Bedrock	-	pegmatite with aplitic granite or aplite		gneissic bedrock	-
Mire	%	3	10	16	-
Slope	%	gently sloping		5 -10	gently sloping

2.1.1. Balsjö: Site specific

The Balsjö experiment is a paired catchment study (Schelker et al., 2013). The scientific name of the study site is 227 Balsjö and the two catchments are the reference area (NR-7) with an undisturbed boreal forest and the clear-cut area (CC-4) in which 64% of the area was harvested in March 2006. In this thesis the two catchments are referred to as Ref and CC for the reference area and clear-cut area respectively. Ref is located about 2 km north of CC, Figure 1. In May 2008 site preparation was performed in CC by disk trenching and caused changes in the understory vegetation from shrub to grass (Schelker et al., 2013). Both catchments are small and very similar when it comes to climate, geology and vegetation, hence the execution of a paired catchment study seemed reliably (Sørensen et al., 2009). The main difference between the catchments is the amount wetlands, Table 1. Differences in inter-annual response between the watersheds are another relevant factor. However, the pre-treatment period (18 months, Sep 2004 - Mar 2006) is too short to distinguish if there is any inter-annual variability (Sørensen et al., 2009).

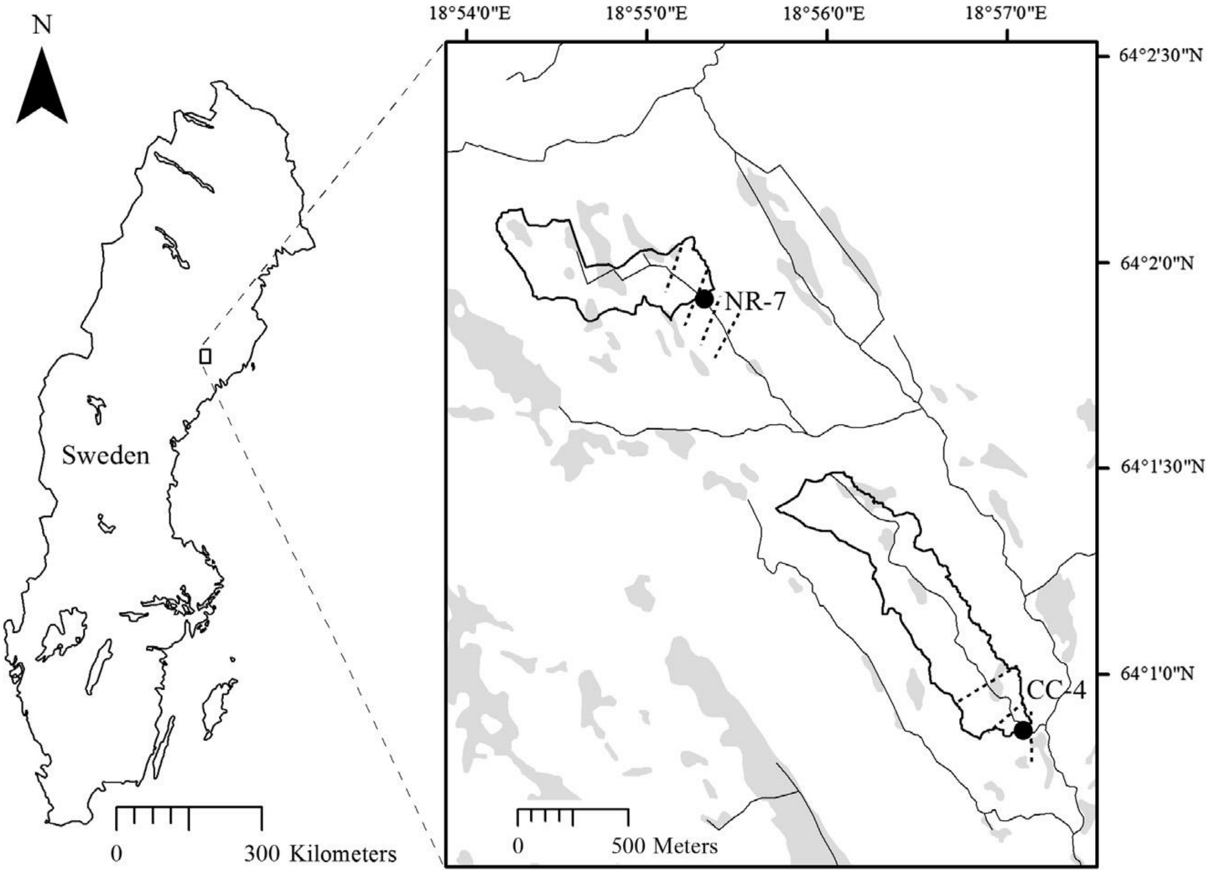


Figure 1. Map over the Balsjö site and the paired catchment experiment (Schelker et al., 2013a). CC-4 is the clear-cut area in this thesis referred to as CC and NR-7 is the reference area referred to as Ref. The black lines mark the catchment boundaries and the grey the stream network whereas the shaded grey areas represent wetlands. The dashed lines mark the snow sampling and the black dots the catchment outlet.

2.2. Field data

A summary of all the data used in this study is presented in Table 2. From Balsjö precipitation, temperature, and discharge from both Ref and CC were used to drive and calibrate the HBV model, as well as the potential evapotranspiration (PET) from Svartberget. The snow water equivalent (SWE) from Balsjö and the ET from Flakaliden were used in the analyses and in the evaluation process.

Table 2. Summary of the data used in this thesis from Balsjö, Svartberget and Flakaliden

		Balsjö	**Svartberget**	**Flakaliden**
	units, resolution	time period	time period	time period
Precipitation	mm, daily	2004-04-13 to 2011-12-31		
Temperature	°C, daily	2003-01-01 to 2011-08-09	1980 – 2007 / 2004 - 2010	
Discharge	mm, daily	2005-04-15 to 2011-05-31 (Ref/CC)		
Potential ET	mm, daily		1986 – 2007 / 2004 - 2011	
ET	Wm^{-2}, 30min			2007 - 2012
SWE	mm	2005 - 2010 (one day each year in late March)		

2.2.1. Balsjö site

Temperature and Precipitation

Direct measurements of precipitation started at the Balsjö study site in 2007. Due to periods of poor data quality the precipitation was interpolated with data from surrounding weather-stations (Hemling, Fredrika, Balsjö-Village, Röbäcksdalen and Krycklan-Svartberget) (Schelker et al., 2013).

The data series of temperature from Balsjö was created in two different ways. The period from 2003-01-01 to 2009-07-31 was made by interpolation between four different stations (Hemling, Umeå, Fredrika och Svartberget). The other period between 2009-08-01 and 2011-05-31 was created from the mean values from dataloggers at site CC-4 and two adjacent sites (Schelker et al., 2013b). The data series from both periods were not continuous and there were several data points missing. The largest periods of missing data were 2004-09-23 to 2004-10-14, 2008-03-27 to 2008-04-10 and 2009-08-01 to 2009-09-16. In order to obtain data for these intervals a correlation of the temperature from Balsjö and Svartberget was done using linear regression. The weather station in Svartberget is located on an open field and not in a forest. The correlation was done on the two separate periods (2004-2009 and 2009-2011) resulting in $R^2 = 0.97$ and $R^2 = 0.99$, respectively. The equations from each correlation were then used to calculate new values to fill in the missing data points from Balsjö.

Discharge

Discharge measurements have been conducted at stream gauging stations located at the catchment outlets since 2004 (Schelker et al., 2013; Sørensen et al., 2009). The data were logged hourly (Schelker et al., 2013). For the HBV model the data were converted and used as daily mean values of specific discharge.

Snow water equivalent

The snow accumulation is measured as snow water equivalent (SWE), and represents the amount of water the snowpack represents, measured in millimetres ($kg \cdot m^{-2} = mm$). The observed SWE values used in this thesis originated from the paired catchment study at Balsjö by Schelker et al. (2013). The snow samplings were conducted during one day in late March every year between the years 2005 and 2010 in both Ref and CC along transect-lines, Figure 1. The total amount of samples varied between 78 and 110 for all years. The distribution of samples between Ref and CC varied as well, but the samples taken in Ref were often more (double amount) than the ones taken in CC (Schelker et al., 2013). There was no large scale sampling in 2011 and therefore no observed SWE from this year was used in this thesis. The purpose of measuring SWE in late March was to try to catch the highest SWE each year. From the measurements made in the Ref and the CC areas a mean value and standard deviation were calculated (Schelker et al, 2013)

2.2.2. Svartberget: Potential evapotranspiration

Potential evapotranspiration (PET) represents the theoretical calculated value of evapotranspiration from an unlimited water source. PET data from Svartberget was used since there was no calculated PET data for Balsjön. This was considered valid since the sites are located close to each other and have similar climate (precipitation). A correlation between temperatures from Svartberget and Balsjö showed that the two locations were in fact similar (see section 2.2.1). In the HBV model PET works as an assumed maximum limit for what is possible for actual evapotranspiration (ET).

2.2.3. Flakaliden: Evapotranspiration

There was no measured ET for Balsjö and therefore the ET from Flakaliden was used. The similarities between the two areas (Table 1) enabled the use. The study site of Flakaliden (site ID: SW2) was established in 1996. The equipment used to measure ET is an eddy covariance tower with a mast of 57 m with the measurement height 43 m whereas the canopy height in 2000 was 8 m (Lindroth, 2004).

The evapotransporation from Flakaliden was given as latent heat flux (LE) in W/m^2 and was converted to mm/day by unit conversion, Equation 1,

$$100\,\frac{W}{m^2} = 100\,\frac{J/s}{m^2} = 100 \cdot \frac{60 \cdot 60 \cdot 24}{\lambda \cdot \rho}\;\frac{kg \cdot J \cdot m^3}{J \cdot m^2 \cdot day \cdot kg} = 3.52\,\frac{mm}{day} \qquad (1)$$

Where the latent heat of vaporization, 2454000 Jkg^{-1} and the density of water, $\rho = 1000\ kgm^{-3}$ at 20 ^{o}C. Some additional data preparations were made. First negative fluxes were discarded, consisting of mostly night-time and near zero values. Second all the data were given as 30 minutes values for the years 2007-2012. To be able to compare the observed data with the simulated data they were transformed into daily mean values by constructing a code in the computer software Matlab which calculated the mean, median and the percentiles: p10% and p90%. The obtained data was incomplete and did not represent 365 days a year. The months that had several days missing are listed in Appendix 2.

There have been several nutritional treatments at Flakaliden over the years, the first one started in 1987 (Lindroth, 2004). It is possible that this could have had an effect on the observed ET. However, the studies have not been performed on the whole area for which ET has been measured.

2.3. HBV model

The HBV model is a conceptual rainfall–runoff model (Seibert and Vis, 2012). The HBV model is developed by the *Hydrologiska Byråns Vattenavdelning* at the Swedish Meteorological and Hydrological Institute, SMHI (Bergström, 1992). The development started in the 1970s and is still an on-going process. The version of HBV used in this thesis was "HBV-light 4.0.0.4" which was developed at Uppsala University in 1993 and is more or less the same as the original version described by Bergström (1992). HBV-light is described by Seibert and Vis (2012). The HBV model is widely applied in research regarding stream-flow response after deforestation in this type of region (Brandt et al., 1988). Even though the HBV model does not require a lot of input data it still manages to give a fairly good estimation of the runoff. These are the reasons why the HBV model was used in this thesis. However it is important to remember that a model can never serve as an absolute truth and the result should therefore only be used as an indication.

The required input data in the HBV model is daily precipitation, temperature and potential evapotranspiration as well as daily discharge (for calibration) (Seibert and McDonnell, 2010). The model simulates discharge using a daily time step. Other outputs are ET, soil water and groundwater storage and SWE.

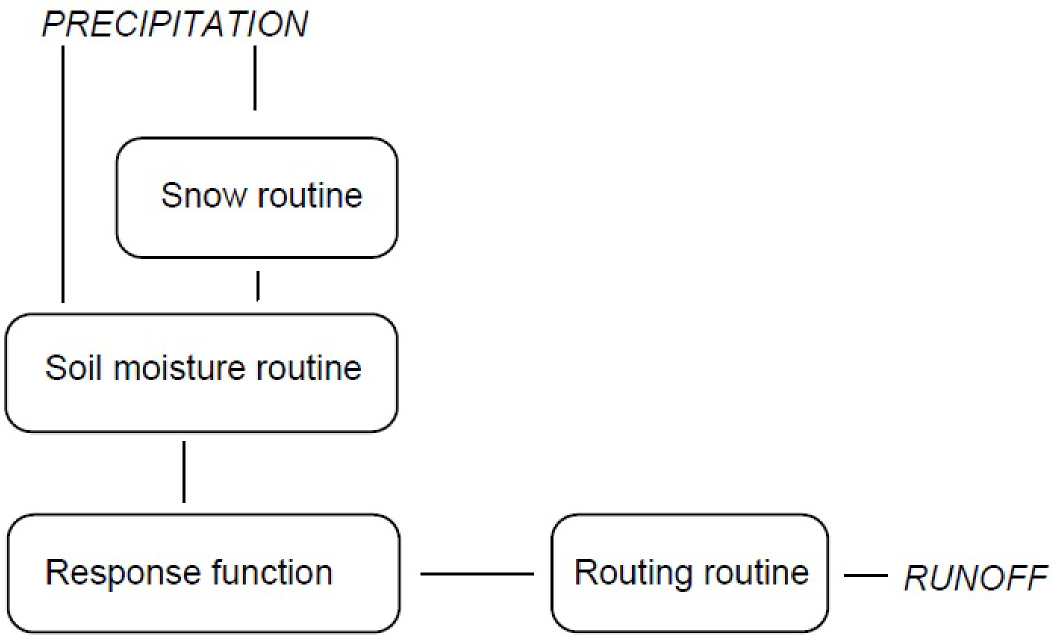


Figure 2. Schematic image over the model structure for the HBV model (HBV-help, 2012)

The model is divided into four routines; snow, soil, groundwater (also called response routine) and routing routine, Figure 2. The response function is divided into two boxes, shallow groundwater (upper storage) and deeper groundwater (lower storage) which both forms the storage groundwater (SG). Each routine is regulated by different parameters and a summary of all the parameters is listed in Table 3 including a short description for each parameter. The parameters that were used to simulate a clear-cut are, TT, CFMAX and SFCF which operate in the snow routine as well as FC, LP and BETA which operate in the soil routine.

The snowfall correction factor (SFCF) has several purposes. First and foremost it compensates for systematic measurement errors related to snowfall (Seibert, et al., 2010). It is also used to compensate for the interception and sublimation of the snow, which it does by subtracting a certain percentage from the precipitation (snow) before it accumulates. The SFCF is usually smaller for forested areas than for open areas.

The HBV model has no separate vegetation routine and does not distinguish between interception, transpiration and soil evaporation. The interception is incorporated in the soil routine in the HBV model as a simplification of the evaporation (Seibert and McDonnell, 2010). In the soil routine the actual evaporation and groundwater recharge, from snowmelt and rainfall, are calculated as functions of actual water storage and maximum soil moisture storage capacity (FC). Higher values of FC indicate a bigger soil water storage capacity and therefore a higher ability for evaporation (Seibert, et al., 2010)

Table 3. The different parameters in the HBV model are listed with a short description (Seibert et al., 2010; Bergström, 1990). The values of the limits are the ones used for the reference area (Ref). The red values have a fixed value and were never altered in the GAP optimization.

Parameter	Description	Unit	Lower bound	Upper bound
Snow routine				
TT	Threshold temperature. If T<TT the precipitation accumulates as snow. Lower TT results in an earlier snowmelt.	˚C	-2	2
CFMAX	Degree-day factor. States how much the snow will melt per degree and day. Lower values for forested areas compared to open areas. A higher CFMAX results in a higher and an earlier peak flow.	mm ˚C^{-1} d^{-1}	0.5	4
SFCF	Snowfall correction factor. It is also the parameter that compensates for the evaporation from the snow storage, where the evaporation mainly comes from interception, but also from sublimation.	-	0.5	0.9
CWH	Water holding capacity.	-	0.1	0.1
CFR	Refreezing coefficient.	-	0.05	0.05
Soil routine				
FC	Maximum of S_{soil} (storage in the soil). Higher FC results in increased evaporation and decreased runoff (occur in late summer and fall).	mm	50	550
LP	Threshold of reduction of evaporation (S_{soil}/FC). Maximum value 1.	-	0.3	1
BETA	Shape coefficient. Parameter that determines the relative contribution to runoff from rain or snowmelt. A higher BETA results in increased evaporation and decreased runoff (occurs during summer).	-	0.4	5
CET	Factor for correction of long-term evaporation rates based on temperature.	-	0	0.3
Response and routing routine				
K0	Recession coefficient (upper storage, saturated runoff). Higher K0 results in higher peak flows with shorter duration.	d^{-1}	0	0.6
K1	Recession coefficient (upper storage, mean flow)	d^{-1}	0.01	0.4
K2	Recession coefficient (lower storage, base flow)	d^{-1}	0.00005	0.1
UZL	Threshold for the K0-outflow. Higher UZL results in lower peak flows with longer duration	mm	0	100
PERC	Maximal flow from upper to lower box. A lower PERC result in higher peaks and lower baseflow.	mm d^{-1}	0	4
MAXBAS	Routing, length of weighting function. Has an attenuated effect on the runoff. A lower MAXBAS results in earlier and higher runoff.	d	1	4

2.3.1. Parameter Optimization

It is generally known that different parameter sets can result in equally good estimations in one simulation, but the estimations may vary tremendously when the parameter sets are tested on another period (Seibert and McDonnell, 2010). In order to optimize the parameter settings, a calibration was made using genetic calibration algorithm (GAP) optimization. The GAP uses an initial population of *n* different parameter sets that are randomly chosen within the allowed boundaries for each parameter. The parameter sets are then evaluated by the value of an objective function (goodness of fit). Thereafter new parameter sets are constructed by combining two of the old ones, which are randomly selected. The higher the fitness of a parameter set is, the higher the probability of being picked. This alternation continues until the requested amount of runs has been made (Bergström, 1992).

Another method to test different parameter sets is Monte Carlo analysis which also randomly selects the values of the parameters. The difference between Monte Carlo and GAP is how they search the parameter space. The GAP is selective and focuses on the parts of the model space, within the parameter limits, where the best parameter fits are. This means that GAP may miss solutions. Monte Carlo only searches randomly for the best solution, and does not "remember" which parameter sets it has already tried, hence the necessary large amount of test simulations for the Monte Carlo method (Seibert et al., 2010). This makes Monte Carlo more reliable, but also less efficient.

2.4. Model calibration/simulations

An overview of used data and how they were used in the modelling process is presented below.

Input HBV

- Daily precipitation from Balsjö
- Daily temperature from Balsjö
- Daily PET from Svartberget
- Daily discharge from Balsjö (Ref or CC)

Calibration and evaluation

- Daily discharge from Balsjö (Ref or CC). The warm up period started from 2004-04-31 for both Ref and CC. The simulation and calibration period was from 2005-04-31 to 2011-05-31for Ref and from the time of clear-cut 2006-03-01 to 2011-05-31 for CC.
- Snow storage in terms of SWE from Balsjö. Measured once a year in late March, from 2005 to 2010
- Daily evapotranspiration from Flakaliden (representing the untreated forest, Ref)

2.4.1. Model settings-Ref

The HBV model was calibrated for Ref in order to find the best parameter sets, giving the most similar simulated values of discharge compared to the observed. This is measured as goodness of fit. When calibrating the model it is appropriate to use as a warm-up period. The recommended minimum warm-up period is at least one year for the HBV model (Seibert and McDonnell, 2010). The warm-up period for Ref was one year and started from 2004-04-31 and ended 2005-04-31 when the simulation and calibration started.

Nash-Sutcliffe, *Reff*, Table 4, is often applied in rainfall-runoff modelling as a measure of goodness of fit. However when using GAP simulation a different function or functions can be used, all measuring the difference between simulated and observed values. Which functions and how they were weighted was decided by trial and error and the notion that the volume error must be considered. After several attempts a combination of the *LindstromMeasure*-function, focusing on high flows and the volume error, and *logReff*-function, focusing on low flows, gave the highest fit (the closest value to 1). The functions were weighted with a factor 0.9 for LindstömMesure and 0.1 for log Reff and the sum of them represented the weighted objective function.

Table 4. Some of the Goodness of fit functions available for the GAP simulation in the HBV model (HBV-Help, 2012)

Goodness of fit function	Description	Definition	Value for perfect fit
Reff	Model efficiency. Concentrates on high flows	$1-\frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-meanQ_{obs})^2}$	1
Lindström-Measure	Lindström measure. Includes the volume error. Concentrates on high flows	$Reff-0.1\frac{\lvert\sum(Q_{obs}-Q_{sim})\rvert}{\sum Q_{obs}}$	1
LogReff	Efficiency for log (Q). Concentrates on base flow	$1-\frac{\sum(lnQ_{obs}-lnQ_{sim})^2}{\sum(lnQ_{obs}-lnmeanQ_{obs})^2}$	1

The weighted objective function was used as a measure of goodness of fit in the calibration of the parameter sets. First, only one GAP calibration run was made, and thereafter an inspection of the parameter values and their limits was conducted. If a value was close to a limit, the limit was widened to allow the parameter values to vary freely. To ensure that the parameter values were not unreasonable, a max- and minimum limit for each parameter were considered before starting the GAP simulation. After the first run a GAP simulation of a 100 different parameter sets was made where the distribution of the parameter values was studied to see if the limits had to be alternated again. After several attempts the limits were adapted to contain most of the possible parameter sets.

In order to ensure that Ref and CC were treated in the same way regarding similar site properties in the HVB model, the parameters that were assumed not to be affected by a clear-cut (K0, K1, K2, UZL, PERC, MAXBAS) were narrowed to simulate a static, specific state for the current catchments. This was a way of forcing the HBV model to treat the two areas as one and to ascertain that differences between the sites depended on the effects of the clear-cut. The parameters were narrowed by using a 95 % confidence interval which was done in Matlab with the command *quantile.* This constriction was also used to avoid potential outliers. The final limits for Ref are presented in Appendix 3.

When the limits for Ref were set, the model was run. As the GAP simulation consisted of 100 different parameter sets, the model did 100 runs that gave 100 of different simulated results. The results files consist of simulated discharge (Q) simulated ET, simulated SWE and simulated soil water storage for the soil box (SM) and the two groundwater boxes SU and SL. In HBV a batch result (a summary of the 100 runs) for discharge is possible to obtain, where the mean, median and the 10% and the 90% percentile are stated. However, there are no batch results for ET, SWE, SM, SU and SL because their results are overrun with each new run. Therefore a Microsoft DOS script (Huseby Karlsen, 2013) was used to contract the 100 result files. To obtain the mean, median, and 10% and 90% percentile for the ET, SWE and the change in storage a Matlab program was constructed which selected the columns in question from each result file and stored them in separate matrixes. From the matrixes the mean, median p10%, and p90% were then calculated.

2.4.2. Model settings-CC

The model settings for CC had a warm-up period of 2 years until the harvesting (March 2006) when the calibration started. To model the CC area in HBV the parameter limits from the Ref calibration were used for the parameters that were assumed not to be affected by a clear-cut (K0, K1, K2, UZL, PERC, MAXBAS). The limits for the other six parameters (TT, CFMAX, SFCF, FC, LP and BETA) were set by the same procedures as before, looking at the distribution of the parameter values, to make sure that it was only the effects of the clear-cut that were being studied. When the limits were set a batch run was performed to get the result files in the same way as for the reference area.

2.5. Data analysis

After obtaining the result files of simulated discharge, SWE, ET and change in soil water storage different analyses were made in order to answer the research questions.

2.5.1. Comparison of simulated and observed runoff

In order to establish how similar Ref and CC were the year before the clear-cut, the period 15-04-2005 to 01-03-2006 was examined. The idea was to see if the parameters from Ref gave a similar fit as of the observed runoff (Q) from CC prior to the harvest.

The average simulated Q for Ref and CC were also compared with the corresponding observed Q for the year 2009 to see how well the HBV model managed to simulate the runoff based on the weighted objective function.

2.5.2. Annual changes in the water balance

To determine whether there had been a change in the water balance between the simulated Ref and CC the annual (1st October - 30th September) water balance was studied. The water balance reads

$$P = ET + Q + \Delta S \tag{2}$$

And for spring (1st April to 31th May)

$$P + SWEss = ET + Q + \Delta S \tag{3}$$

where P is the precipitation (mm), SWEss represents the snowpack when the spring period starts (mm), ET stands for evapotranspiration (mm), Q is the runoff (mm) and ΔS represents the change in soil water storage (mm). Focus has been on the year 2009, which had an expected behaviour, and the year 2010, which illustrated unexpected runoff behaviour (Schelker et al., 2013). The total sum of the simulated average values of the annual Q, ET and change in soil water storage in terms of SM (storage in the soil box) and SG (a combination of storage of the two groundwater boxes) were compared for Ref and CC for both 2009 and 2010. The potential difference between the total sum and the corresponding precipitation was believed to be the water losses through interception and sublimation of snow shown by the snow correction factor, SFCF, in the HBV model.

2.5.3. Spring period

For the spring period (1 April to 31 May) the simulated data of discharge, SWE, ET and change in storage (ΔS) were compared with the available measured data. The comparisons were performed in order to account for the different pathways of the water and to shed light on the unexpected runoff behaviour that was registered in Balsjö in spring 2010. The ΔS was presented as the sum of the changes in soil water box (ΔSM) and the two groundwater boxes (ΔSG) in the HBV model. The comparison between simulated and observed data of SWE and ET can also be seen as an evaluation of the model.

In order to capture the dynamics of the variables and to be able to account for the different pathways of the precipitation summary plots were made of the SWE, Q, ET and ΔS for the same time period. This was also a way to get more insight in how the HBV model simulates the different variables.

2.5.4. Comparison of simulated and observed SWE

The simulated SWE and the observed SWE were analysed further as well as the difference in snow accumulation between Ref and CC area. This was done by plotting the simulated difference between simulated SWE for Ref and CC.

2.5.5. Comparison between simulated ET and observed ET

The simulated ET from the Ref and CC were further investigated to see the effect of a clear-cut. A comparison between the observed ET from Flakaliden and the simulated ET from Ref was made to distinguish how the HBV model managed to simulate ET when it came to dynamics, timing and magnitude.

2.5.6. Comparison of parameter sets between Ref and CC

Another way of examining how the HBV model manages to simulate a clear-cut is by comparing the parameter sets for Ref and CC with the values of the limits median/mean to see if the differences between the parameters could be supported by the literature and expectations. Hopefully, the change of the parameters can shed light on the why and how, for example, peak runoff increases during snowmelt.

In order to distinguish if the parameter values for the two catchments are significantly different the Wilcoxon Rank-sum test was used. Wilcoxon rank-sum is a non-parametric test, which means that it can be used on data that are not normally distributed. Rank-sum is used when the data are assumed to be independent. The test is used to analyse if two data sets are significantly separated, namely if they do not have the same median. Before the test is conducted a value of α is chosen. α represents the allowed error, and the standard value is set to 0. 05 which means that the probability of the null hypothesis (H0) is dismissed, even if it is true, is 5%. The null hypothesis states that the two data sets have the same median value. The test generates a significance level (p value) and if $p \leq \alpha$ H0 can be dismissed (Helsel & Hirsch, 2002).

2.5.7. Relation analysis between simulated discharge and climate parameters

Finally the relationship between the simulated clear-cut effect and the observed climate parameters (P, SWE and ET) was investigated. The clear-cut effects were illustrated as the difference between the simulated runoff from CC and Ref. The purpose of the relation analysis was to see during which weather conditions the clear-cut had the most effect on the discharge. Perhaps the climate can explain the differences in the runoff behaviour for some years (2010 and 2011) compare to other years.

3. Results

3.1. Data analysis

3.1.1. Comparison of simulated and observed runoff

In the year before clear-cut the parameters from the reference area (Ref) gave a similar fit for the observed Q from the clear-cut area (CC) as for the observed Q from Ref, Figure 3. The weighted objective function was 0.710 for CC and 0.660 for Ref.

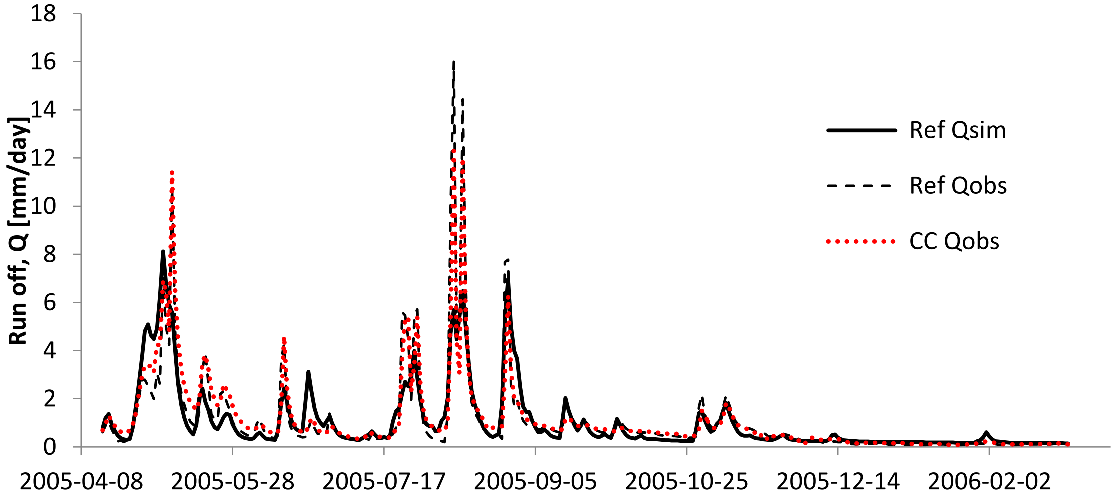


Figure 3. Simulated runoff (Ref Qsim) for the reference area compared with the observed runoff for the reference area (Ref Qobs) and the clear-cut area (CC Qobs) before it was clear-cut.

The capacity of the HBV model of simulating the runoff for the two catchments was considered adequate when examine the years 2009, Figure 4, and 2010, Appendix 4. The weighted objective function was higher for Ref than for CC with a mean value of 0.7344 and 0.6998 respectively. This was expected since the calibration done for Ref allowed all the parameters to vary more freely, whereas for the calibration of CC, some of the parameters were more limited. The distribution of the weighted objective function is presented in Appendix 3.

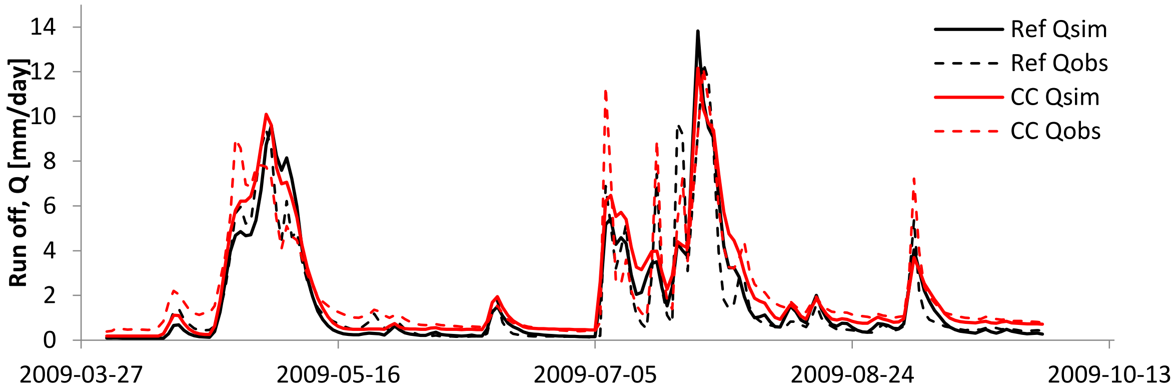


Figure 4. Comparison between simulated (Qsim) and observed (Qobs) runoff for the reference area, Ref, and the clear-cut area, CC, for 2009 (1 April - 30 September).

3.1.2. Annual and spring water balance

A summary of the simulated data analyses is presented in Table 5, where the precipitation, P, is observed values while other variables are simulated values for Ref and CC. There are no annual values for 2006 and 2011 because of incomplete data series. For 2006 the simulation of the CC did not start until after the clear-cut in March 2006 and therefore the data series do not represent the whole hydrological year. The reason for incomplete data series for 2011 is that the input data in terms of observed discharge ended in late May 2011. The simulated SWEss for each year were selected for the same date as the corresponding observed SWE. There are no observed values of SWE for the year 2011. The presented simulated value represents the 31 March since all the observed values for the previous years were taken around this time.

For all examined years (2007 - 2010) the annual runoff was higher for CC than Ref and the annual ET was higher for the Ref than for CC. The annual change in storage, ΔS (combination of the change in the storage of the soil box (ΔSM) and the two groundwater boxes (ΔSG) in HBV) varied between the years and the areas. Generally the CC had a more negative change in soil water storage than the Ref. The only year with a positive change was 2010. The largest difference between the sites occurred in 2008 which also stand out as the year with the largest change for both the Ref area and the CC area (2008 was also the year with the least precipitation).

For the spring period the results are not as consistent, with more variations between the sites, and with 2007 standing out as a divergent year. The SWEss and the runoff were higher for CC than Ref for all years except for 2007 when the SWEss and the runoff were higher for Ref. The ET was higher for Ref than for CC for all years. The change in storage was negative for all years for Ref whereas 2006, 2010 and 2011 had a positive change for the CC.

Table 5. The total annual and spring values of observed precipitation (P) and simulated runoff (Q), evapotranspiration (ET), snow water equivalent (SWEss), which represents the value of the snowpack when the spring period starts, and change in storage (ΔS). All the parameters are presented in mm.

Ref	**Annual (1Oct-30Sept)**				**Spring (1April-31May)**				
	P	Q	ET	ΔS	P	SWEss	Q	ET	ΔS
2006		-	-	-	96	56	104	55	-5
2007	716	433	207	-7	51	83	113	62	-46
2008	552	305	204	-35	41	137	140	54	-22
2009	668	375	232	-4	56	106	116	66	-25
2010	647	352	206	18	65	113	132	51	-10
2011		-	-	-	71	100	102	71	-7
CC									
2006		-	-	-	96	63	113	42	14
2007	716	534	146	-10	51	64	91	51	-38
2008	552	421	140	-48	41	157	161	42	-7
2009	668	485	159	-13	56	129	136	48	-1
2010	647	458	143	10	65	138	142	41	18
2011		-	-	-	71	114	113	52	14

To distinguish any possible changes in the annual water balance the observed precipitation and the simulated evapotranspiration, runoff, and change in soil water storage were examined, Figure 5. The investigated years were 2009 and 2010 since they were believed to be years with an expected respectively unexpected runoff behaviour. The difference between the measured annual precipitation and the sum of the simulated annual average runoff (Q), ET and ΔS was accounted as the snow losses from the snow fall correction factor in the HBV model. The observed P is used as an input in the HBV model. But if the temperature is lower than TT the precipitation is accounted for as snow fall. Then the snow fall is multiplied with the correction factor (SFCF) which compensates for systematic measurement errors and for the interception and sublimation of the snow. This correction means that some of the snow fall is subtracted from the system. The remaining snow fall represents the input for the water balance and results in the simulated values of Q, ET and ΔS. The parameter value for SFCF is consistent for the whole simulation period (all five years) and does not change between years.

In 2009 the annual water balance showed the expected pattern with a lower runoff and a higher evapotranspiration in Ref than for CC. The change in storage was minor for Ref and negative for CC. For 2010 the changes in storages was higher for Ref than CC. Otherwise the same pattern was shown as for 2009 with a lower runoff and a higher evapotranspiration for Ref than CC.

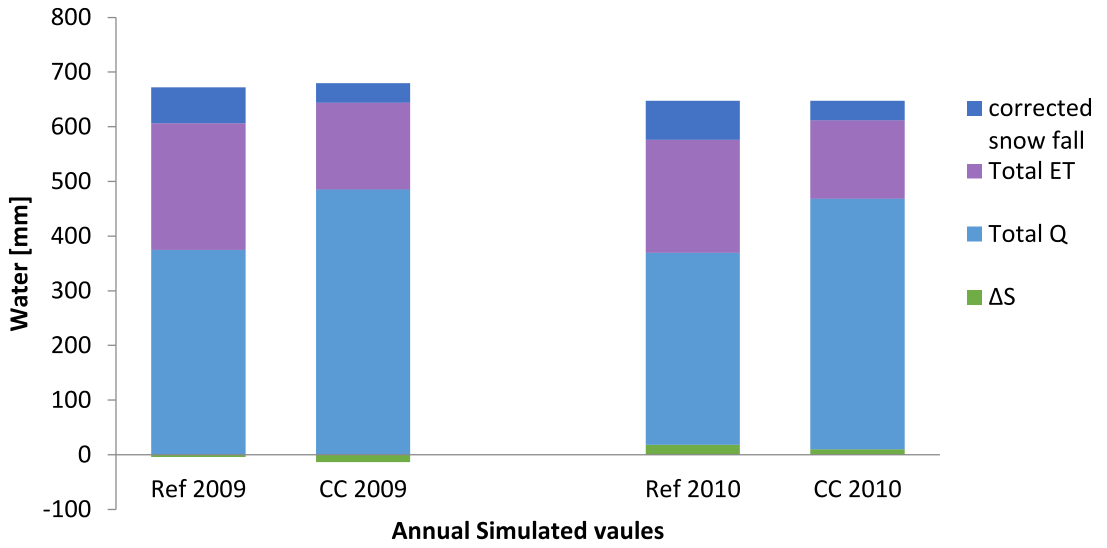


Figure 5. The total sum of the average simulated values of the annual Q, ET and change in storage in terms of ΔS were used to compare Ref with CC for 2009 and 2010. The difference between the total sum and the corresponding precipitation was the water losses from the snow correction factor (SFCF) in the HBV model.

3.1.3. The spring period

For the spring period (1 April to 31 May) the same two years (2009 and 2010) were studied. The total sum of the variables snow water equivalent, runoff, evapotranspiration, and change in storage of both simulated and observed values were compared for both catchments, Figure 6 (2009) and Figure 7 (2010). The observed SWEss was a mean value from snow samples taken during one day in late March each year with the purpose of catching the highest value for the accumulated snow which also represents the starting value for the spring period. In order to make a comparison between the observed and simulated values, the simulated values for the same day were used.

In 2009 the SWEss in CC was higher than Ref for both the simulated and observed values even though the simulated values were lower than the observed, Figure 6. The same applied for the runoff although the difference between simulated and observed values was smaller. The simulated ET was higher for the Ref than the CC. The simulated ET for the Ref was comparable with the observed one from Flakaliden. The change in storage was negative for Ref while close to zero for the CC.

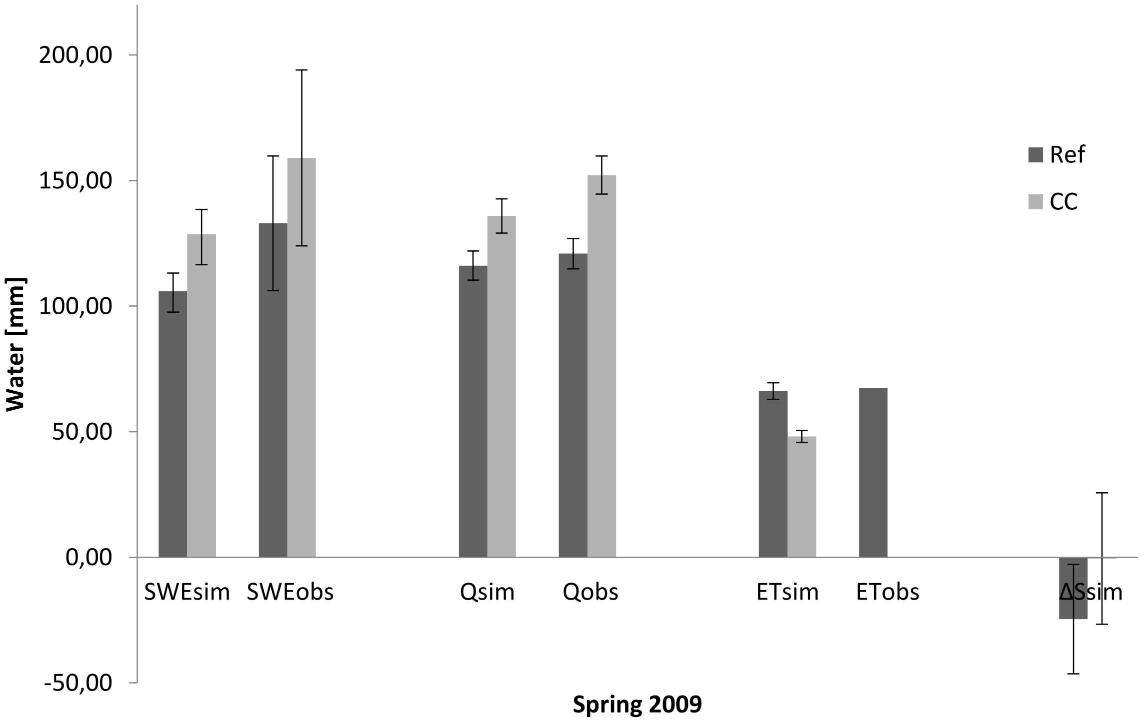


Figure 6. The sum of both simulated and observed average values for the variables SWE, Q, ET and ΔS for the spring period in 2009 for the reference area (Ref) and the clear-cut (CC).

Also in 2010 both the simulated and the observed SWE were higher for the CC than Ref. The simulated values were also lower than the observed (Figure 7). The year 2010 was the year with unexpected runoff behaviour, where the difference in accumulated snow between the Ref and CC could not be seen in the corresponding observed runoff. For the simulated runoff the difference between Ref and CC were small (10mm). The simulated ET was higher for the Ref than the CC as for 2009 although with lower values than for 2010. A comparison between the simulated ET for Ref and the observed ET from Flakaliden showed that the observed value was lower, almost as low as the simulated value for CC. The change in storage was negative for Ref, as for 2009, but smaller. The change in storage was positive for the CC and significantly larger than 2009. However, the difference between the Ref and CC in storage was similar for 2009 and 2010, Table 5.

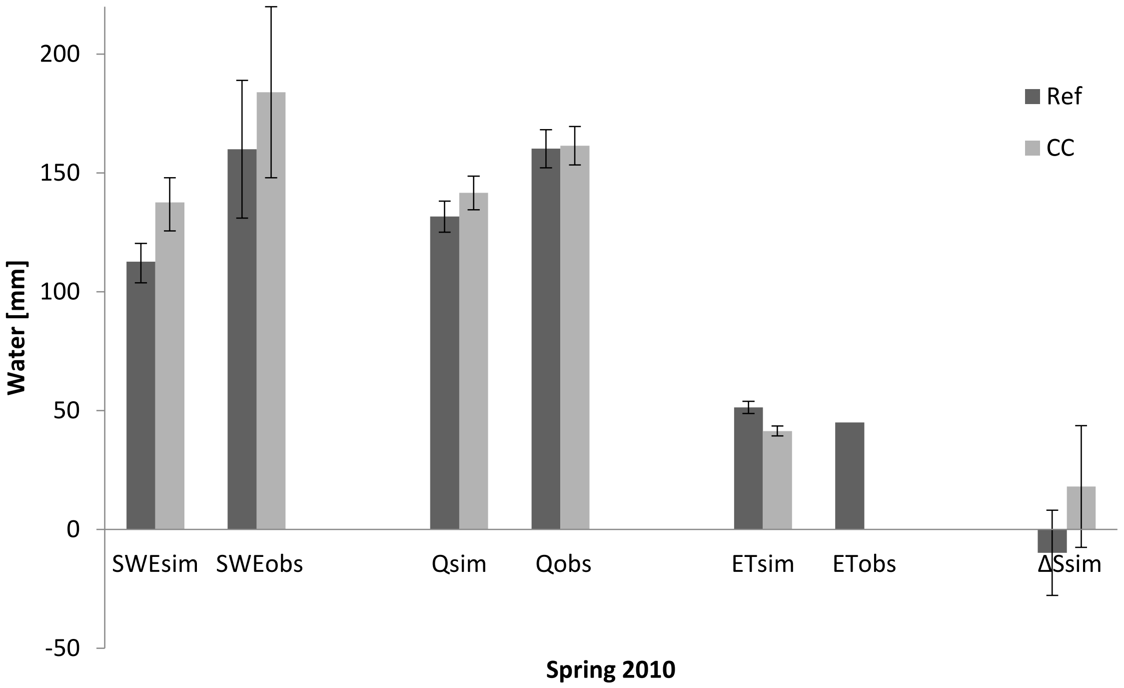


Figure 7. The sum of both simulated and observed average values for the variables SWE, Q, ET and ΔS for the spring period in 2010 for the reference area (Ref) and the clear-cut (CC).

The differences between Ref and CC for the different simulated parameters are between 10 to 28 millimetres for the spring period, Table 6.

Table 6. The differences between CC and Ref for the simulated parameters, ΔSWEsim, ΔQsim, ΔETsim and ΔSsim are presented as absolute values and as the difference between CC and Ref in the brackets (CC-Ref).

Differences between CC and Ref (spring)	**ΔSWEsim**	**ΔQsim**	**ΔETsim**	**ΔSsim**
2009	23	20	18 (-18)	24 mm (-24)
2010	25	10	10 (-10)	28 mm (8)

The dynamics of the simulated variables for 2009 and 2010 is presented in summary graphs, Figure 8 and Figure 9. When the snow melts a corresponding runoff peak appears. In 2009 the SWE in CC was higher than in Ref. The snow also melted faster in CC, resulting in an earlier and higher runoff peak flow compared to Ref. Even in the change of storage the effects of the snowmelt was seen as a similar peak as for the runoff. The ET for the CC had a higher initial peak than the Ref, but thereafter Ref had consistently higher values.

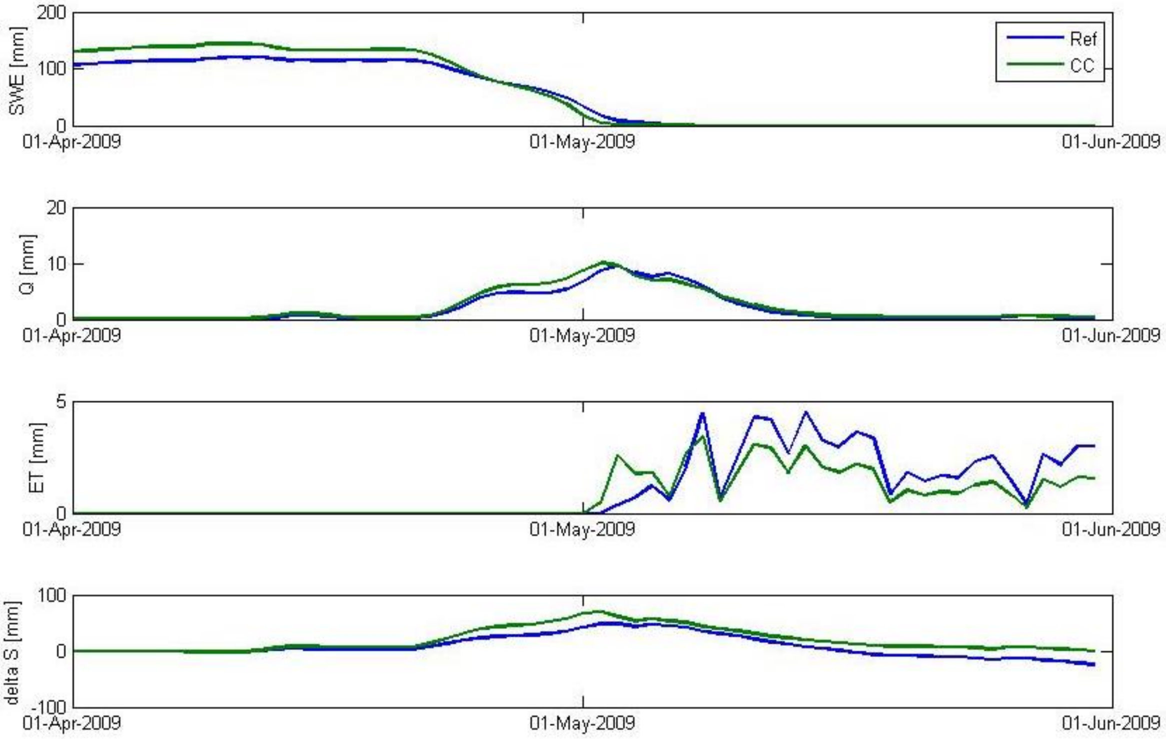


Figure 8. Summary graphs of the simulated average of the variables SWE, Q, ET and ΔS for the spring period of 2009 for both CC (green) and Ref (blue).

For 2010 the accumulated snow had the same behaviour as in 2009 with a higher SWE and an earlier snowmelt for CC than for Ref. However, the snowmelt spanned over a longer period than for 2009. Nonetheless, the runoff in 2010 had an unexpected appearance with an earlier peak for CC, but considerable lower than for Ref. The behaviour of ET was similar as for 2009. There was a larger difference in soil water storage between CC and Ref in 2010 than in 2009.

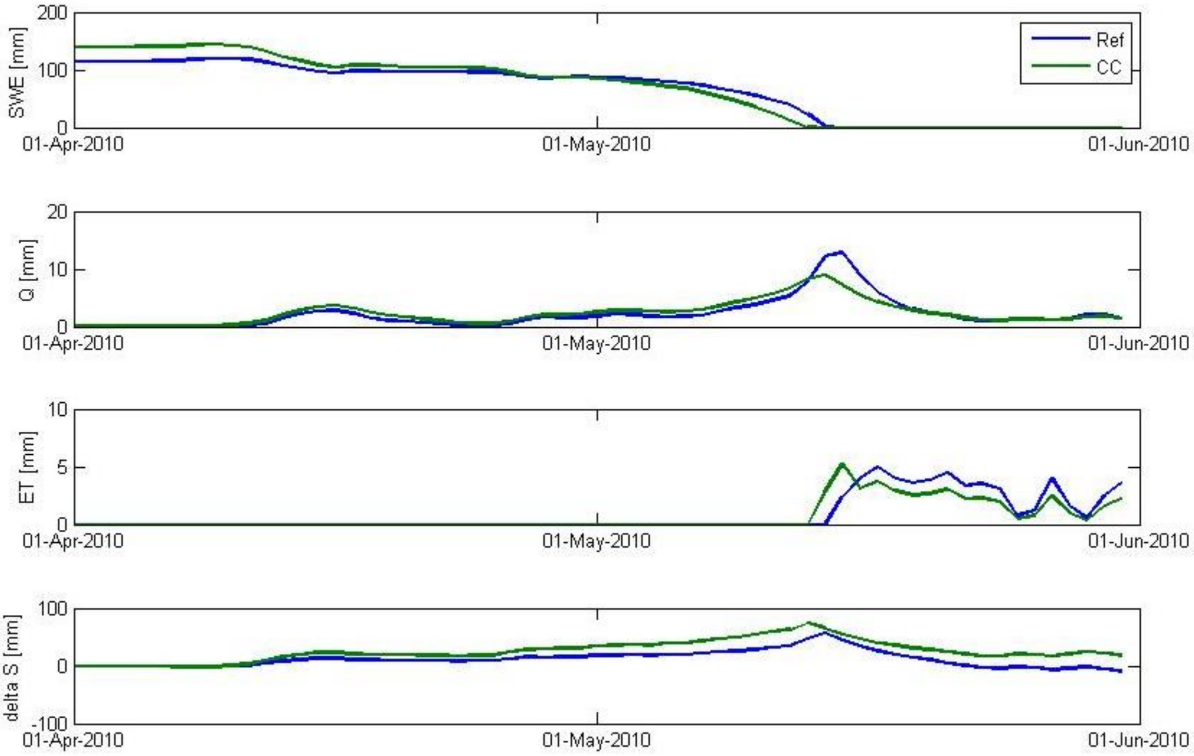


Figure 9. Summary graphs of the simulated average of the variables SWE, Q, ET and ΔS for the spring period of 2010 for both CC (green) and Ref (blue).

3.1.4. Comparison of simulated and observed SWE

As seen earlier the simulated SWE for both Ref and CC gives an underestimation compared to the measured data for almost every year, Figure 10. There were no observed SWE for the year 2011.

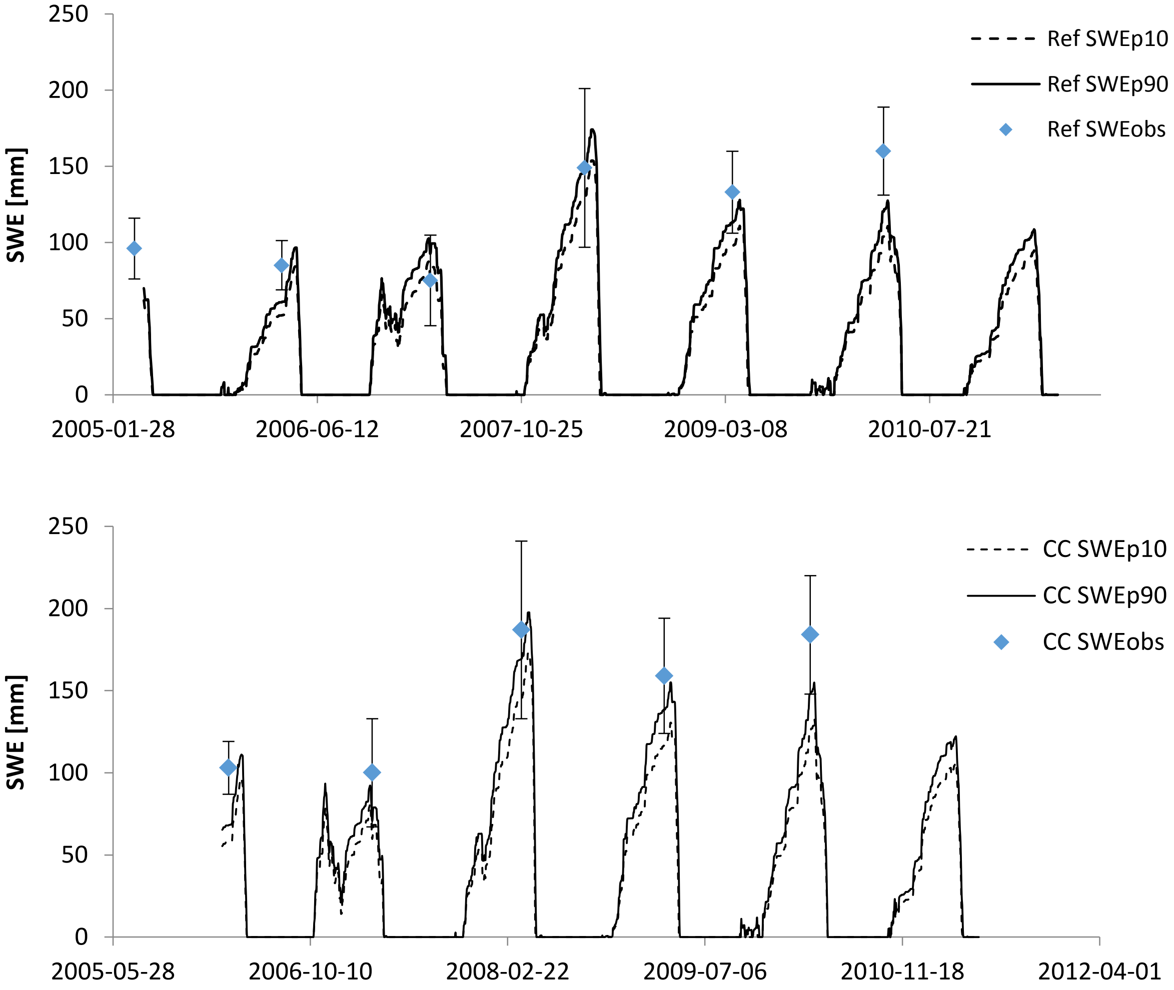
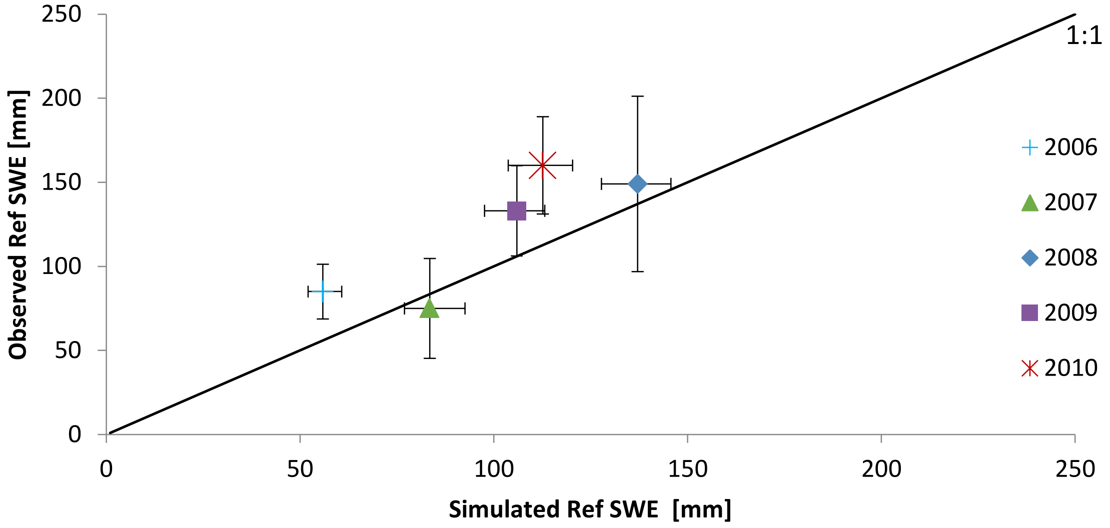


Figure 10. SWE for the reference area, Ref (upper) and the clear-cut area, CC (lower) respectively. The simulated SWE is presented as 10 and 90 percentiles together with observed SWE which is the mean values of the different snow samples taken one day each March. The error bars represent the standard deviation of the observed values.

As another way of comparing the simulated and observed SWE a scatter plot was made with the simulated SWE on the X-axis and the observed SWE on the Y-axis. For both Ref and CC the observed values were undoubtedly higher than the simulated with one exception in 2007 in Ref, Figure 11. The year of 2008 stood out as the year with the highest simulated snow accumulation in in Ref as well as in CC. This year had also the largest standard deviation of the observed values. The largest observed values were found in 2010 whereas the lowest were found in 2007 (for both catchments).



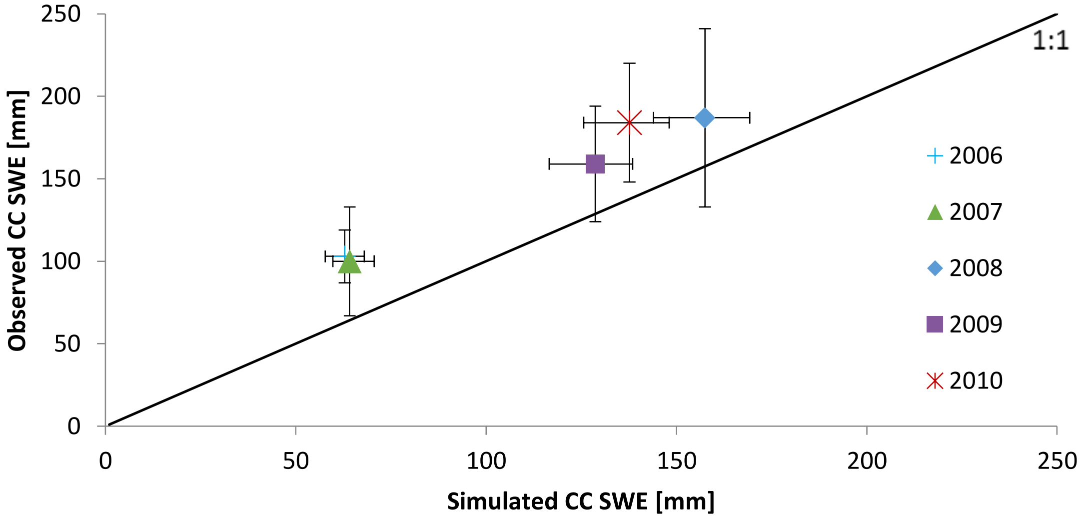
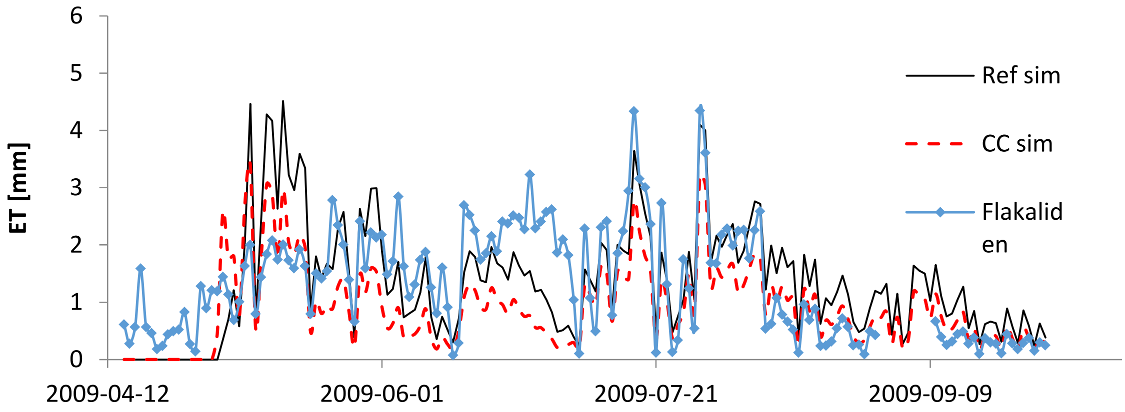


Figure 11. The observed and corresponding simulated SWE values for the years of 2006 until 2010 for the reference area, Ref (upper) and the clear-cut area, CC (lower). The error bars indicated the standard deviation for the observed SWE while as the error bars of the corresponding simulated value presented the tenth and the ninetieth percentile.

3.1.5. Comparison between simulated ET and observed ET

The simulated ET shows that the ET was higher for Ref than for CC, for both 2009 and 2010, Figure 12. A comparison between observed ET from Flakaliden and the simulated for both Ref and CC for the years 2009 and 2010 indicated that the HBV model generally underestimate the observed ET. The simulated values were zero until the middle of May and therefore the investigated period started from May until September, to be able to compare simulated values with observed.



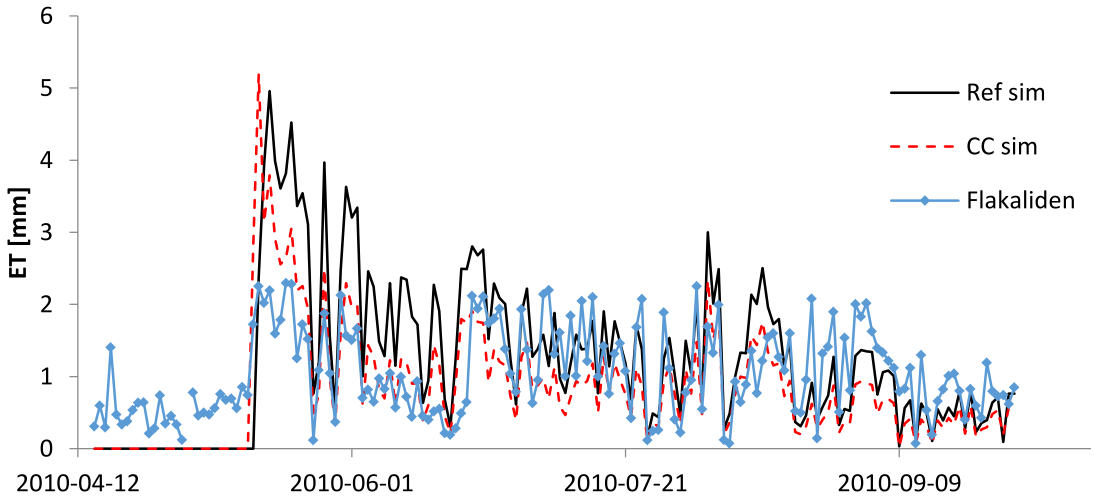
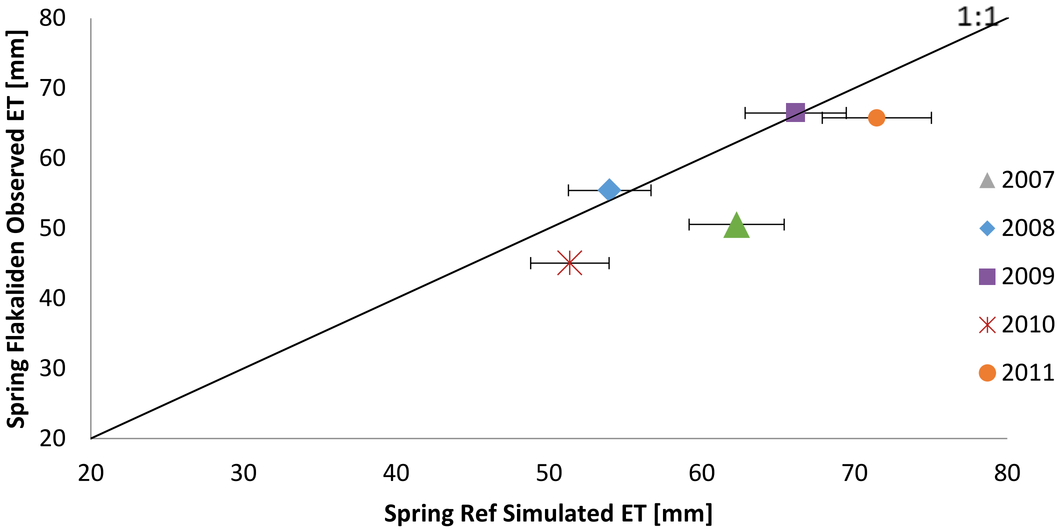


Figure 12. The evapotranspiration, ET for the period 15 April - 30 September for the years 2009 (upper) and 2010(lower). The observed ET from Flakaliden is presented as a blue line with dots. The simulated average ET is shown for both the reference area and the clear-cut as Ref sim and CC sim.

That the HBV model underestimates the ET became clearer by looking at a scatter plot of the sum of average ET values for the simulated values from Ref and observed values from Flakaliden, for the spring period, Figure 13 (upper). On the other hand it also showed that the model manages almost a perfect match for the year of 2008 and 2009. On the contrary the annual values showed the opposite with an overestimation for some years, Figure 13 (lower)



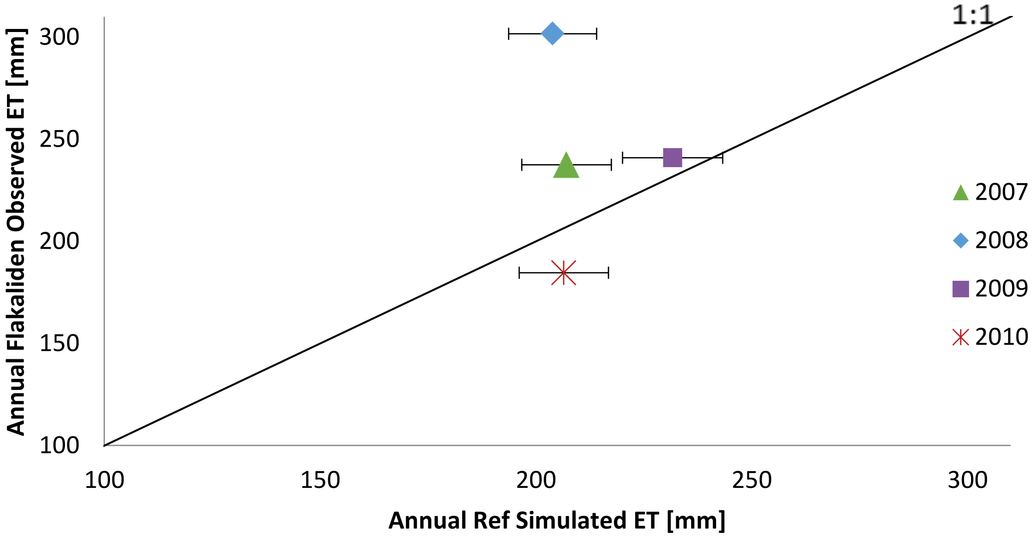


Figure 13. Comparison between the sums of average simulated and observed ET values for the spring (upper) and the annual (lower). With the simulated ET from the reference area on the Y-axis and observed ET from Flakaliden on X-axis. The error bars for the simulated values represent ±5% of the value. There are no error bars for the observed because of the missing values.

3.1.6. Comparison of parameter sets between Ref and CC

To see how the HBV model simulates a clear cut the distribution of the parameter set of Ref and CC were analysed. The complete distribution of the all the parameters with percentiles [0.025, 0.25, 0.50, 0.75, 0.95] is shown in the Appendix 3. The main focus of the analysis was on the six parameters that were assumed to be affected by a clear-cut (TT, CFMAX, SFCF, FC, LP and BETA). The differences in these parameters for the two catchments are described in Table 7. In order to determine if the parameters representing Ref and the parameters representing CC are significantly different the Rank-sum test was used which generated p-values for each parameter. When $p \leq 0.05$, the parameters for Ref and CC were considered significantly different. A complete list of all p-values for all of the parameters is shown in Appendix 3. For all of the parameters that were assumed to be affected by a clear-cut the p-values were below 0.05 except for the threshold temperature (TT) which had more or less the same median value for both catchments, Table 7.

Table 7. The difference of the parameters between the reference area, Ref and the clear-cut area, CC. The parameters were compared using their mean values. The area with the highest average is marked red. The p-value indicates if the difference in a parameter value between the sites is significant.

Parameter	Ref	CC	p-value	Comments
TT	0.46	0.45	0.49	The values of TT were almost same for the two catchments and were not significantly different.
CFMAX	1.62	2.43	<0.01	The CC had a significant higher CFMAX than Ref which is expected for an open area compared to a forest, a larger CFMAX usually also gives a higher peak flow.
SFCF	0.70	0.83	<0.01	Even the SFCF for CC was higher than for Ref. The SFCF affects the snow as *Snow = Precipitation x SFCF* which means lower SFCF results in less snow. This agrees with the general situation the forest has less snow than a clear-cut.
FC	104.4	60.9	<0.01	FC was higher for Ref than CC. A higher FC increases the soil water storage. This may enable higher evaporation, but that is highly related to LP. A higher FC indicates a higher evaporation and a lower discharge which is expected when comparing a forest to an open area.
LP	0.90	1.00	<0.01	LP is the fraction of FC, at which the actual ET reaches PET. Actual ET is calculated as a function of soil moisture, the more water available the easier it evaporates. LP controls when the actual ET becomes maximum. LP has a maximum value of 1.
BETA	0.83	0.35	<0.01	A higher BETA indicates a higher evaporation and a lower discharge

The distribution of the parameters showed a difference between the two areas. A difference that could be detected for both those parameters that should not be affected by a clear-cut, Figure 14(upper), and thus how should, Figure 14(lower). Some of the parameter values were spread over a wider span for both Ref and CC, for example UZL. The parameters PERC and MAXBAS for CC appeared to want to break free from the narrowed boundaries. The same behaviour seems to apply for the LP parameter which is one of the parameters assumed to be affected by a clear-cut. The assumed affected parameters were allowed to vary freely, the reason for LP's behaviour is that the parameter can take a maximum value of 1 in the model.

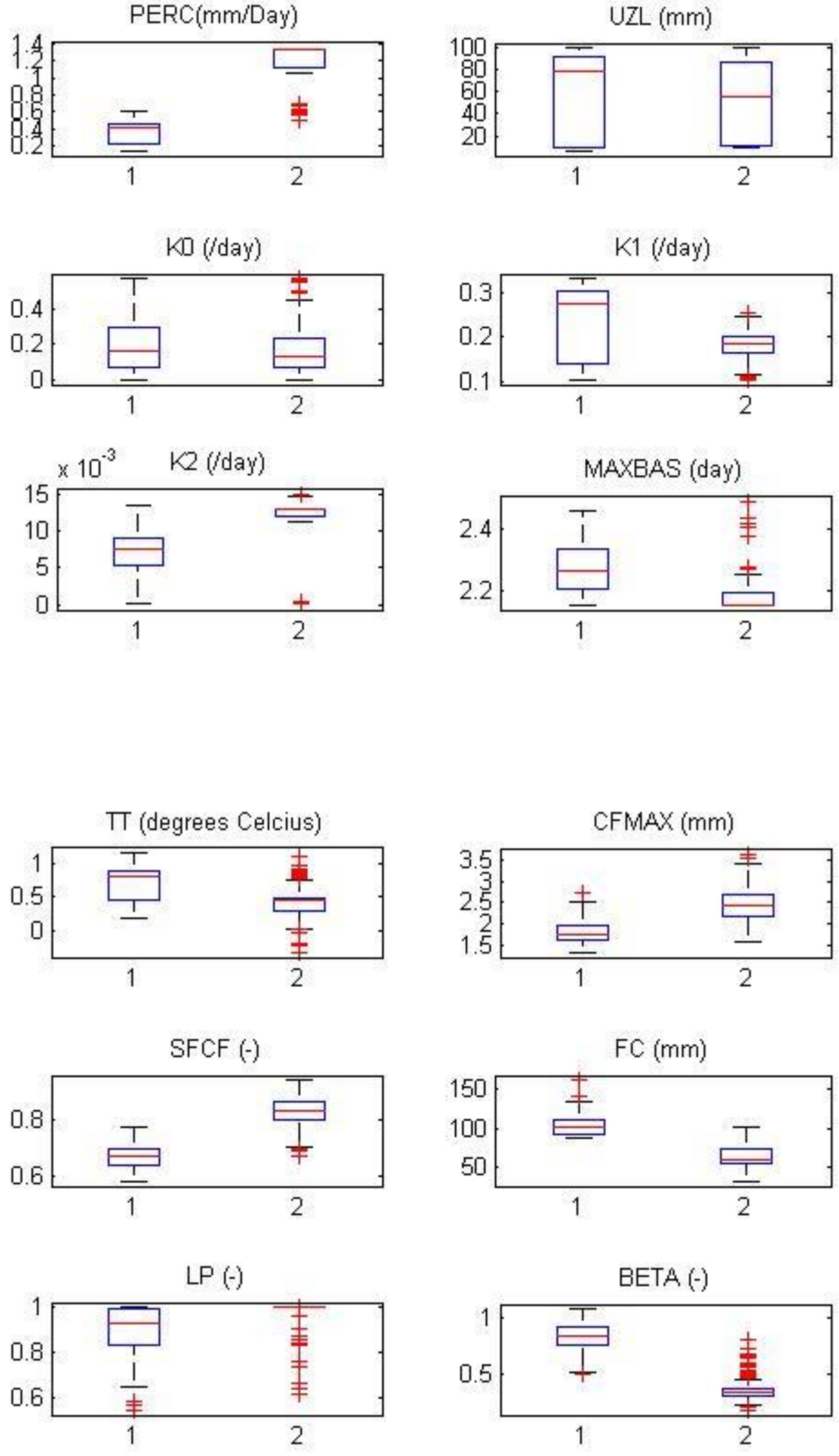


Figure 14. Parameters that were assumed not to be affected by a clear-cut (upper) and parameters that ought to be affected by a clear-cut (lower). The reference area (Ref) is marked as 1 and the clear-cut area (CC) as 2.

3.1.7. Relation analysis between simulated discharge and climate parameters

The relation analysis consisted of too few data points (years) to make a statistic analysis and were therefore only used as an indication. The annual analysis between the simulated clear-cut effect and the observed climate parameters (P, and ET) showed a negative association, Figure 15. Years with less precipitation seems to result in higher effects, namely an increased difference in runoff between CC and Ref. For evapotranspiration, the effect seemed to be higher for years with higher ET. However, the year 2007 did not follow this pattern for ET. The same year stand out as a year with a low effect.

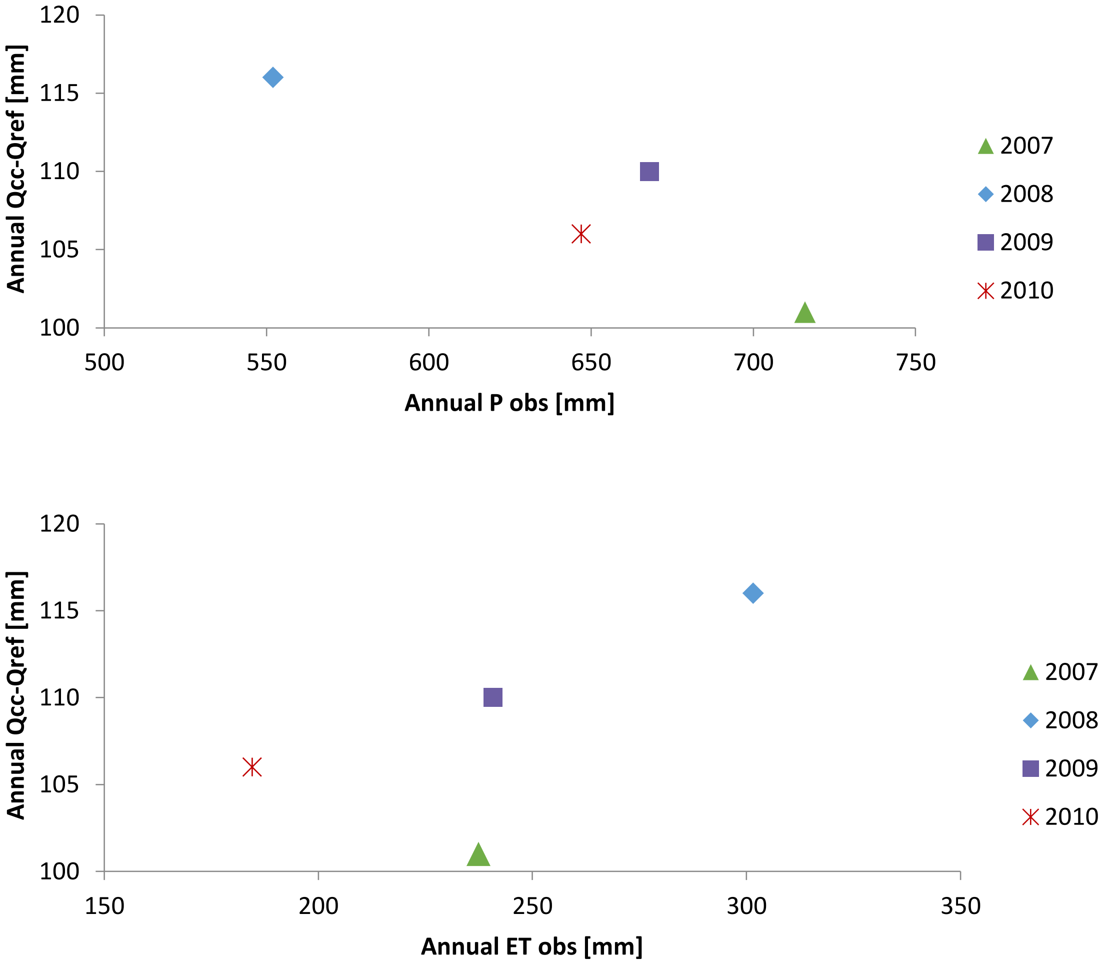
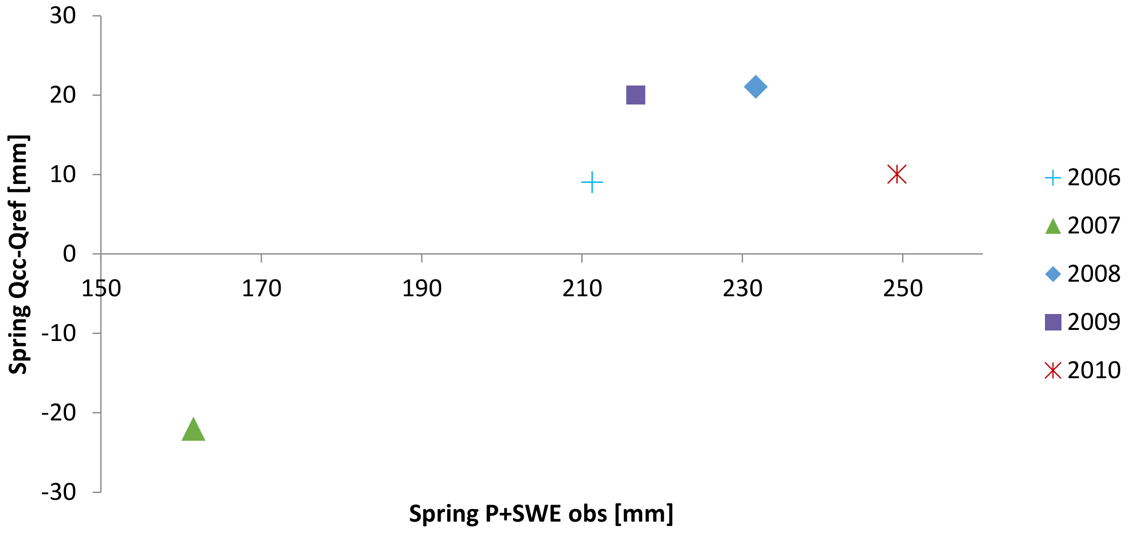


Figure 15. Annual relation analysis between simulated clear-cut effects and observed climate parameters. The effect is represented as the difference between the simulated runoff from the reference area and the clear-cut (QRef-QCC) on the Y-axis, and the observed precipitation, P, (upper) and ET (lower) on the X-axis.

The spring analysis showed no relationships between simulated effects and climate parameters (P+SWE and ET), Figure 16. The spring period of 2007 stands out even more as the only year with a negative effect. This was because Ref had a higher runoff and a lower ET than CC for this year. This means that 2007 had an unexpected runoff behaviour after a clear-cut. A behaviour that became clearer when studied the spring period.



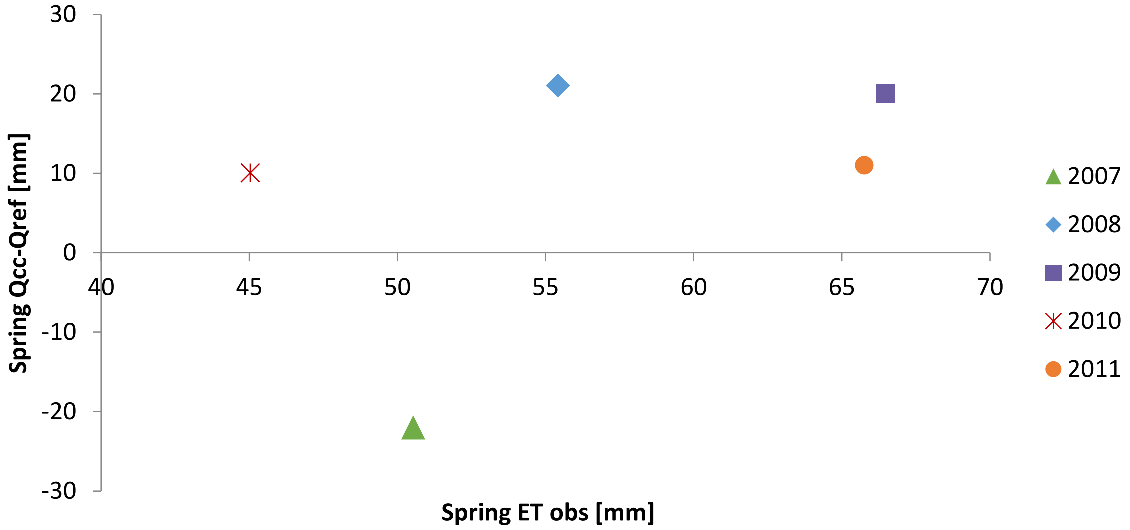


Figure 16. The spring relation analysis between simulated clear-cut effects and observed climate parameters. The effect is represented as the difference between the simulated runoff from the reference area and the clear-cut (QRef-QCC) on the Y-axis, and the observed precipitation, P, combined with the observed SWE (upper) and ET (lower) on the X-axis.

4. Discussion

4.1. Data analysis

4.2.1. Comparison of simulated and observed discharge

By studying the year before the clear-cut the notion that the two catchments, Ref and CC, can be treated as one seems to be justified. This was because the simulated Q generated from calibrated parameters from Ref gave a similar fit for the observed Q from the clear-cut as for the observed from the reference area. However, this can only be seen as an indication since one year is too short period of time to make a substantial statement. The fact that the weighted objective function gave a higher value for the observed runoff from the clear-cut area than the observed runoff from the reference area was at first surprising. The reason for this was believed to be that since the parameters were calibrated for the whole period for the reference area, some years will get a better fit than others and 2005 was a year that gave a lower fit than the general.

A comparison of simulated and observed discharge for the two catchments showed that the HBV model manages to simulate the runoff quite well. This was expected since the calibration of the model was done for the whole time period (2006 - 2011) for both the Ref and CC. This was done because the task was not to predict the runoff for Balsjö in the future but to see what have happened during the actual time period in terms of SWE, ET and soil water storage.

The reason why the model does not get an even better fit is that the variations in runoff between the years are big and the model simulates something in between. This means that the model misses some of the differences between the years and therefore does not get the same result as seen in observed data by Schelker et al. (2013).

4.1.2. The annual and spring water balance

The unexpected runoff behavior of 2010, with no difference in runoff between the two catchments despite a large difference in accumulated snow, could not be detected in the simulated values. This was clear after examining the sum of the simulated annual water balance and the spring period. The snow accumulation and runoff were higher for CC than Ref for both the annual and the spring period. The evapotranspiration was also consistent with higher values for Ref than CC. The reason why the unusual runoff behavior for 2010 was noticed in the observed data (Schelker et al., 2013) and not in the simulation is not clear. Perhaps the HBV model did not manage to simulate the runoff good enough and thereby missed the irregular behavior in the clear-cut catchment.

4.1.3. The spring period

The unexpected runoff behavior of 2010 was seen for the spring period in Figure 7 where the observed runoff was the same for the two catchments whereas the snowpack was higher in CC than in Ref. The simulated values for 2010 for the spring period, Figure 7, showed an indication of the unexpected runoff behaviour since the difference in runoff between the two catchments was small. The difference in SWE between the two catchments for spring 2009 and 2010 was 23 mm and 25 mm respectively, while the differences in runoff were 20 mm and 10 mm, Table 6. Even though this could be interpreted as an unexpected runoff behavior in 2010 the magnitude of the difference between the catchments should be considered. A difference of 25-10 mm seems to be small and was perhaps only the result of measurement and simulation errors.

The comparison between the simulated ET for Ref and the observed ET from Flakaliden for 2010 showed that the observed value was lower than the simulated value, almost as low as the simulated value for the clear-cut area, Figure 7. One explanation for this is, as mentioned earlier, that there were several days of missing values for the observed ET and thereby the result is questioned.

The unexpected runoff behavior of 2010 was easier to detect when studying the simulated dynamics of the variables in Figure 8 (2009) and Figure 9 (2010), where the runoff in 2010 had a higher peak in Ref than in CC. However, the behaviour of ET seemed to be similar as for 2009 where the ET was higher for Ref than CC for the total spring period. The difference in duration for the meltperiods between the two years may be of interest. For 2009 the meltperiod ended in the beginning of May, while it lasted until the middle of May for 2010. Maybe the ET was higher for the clear-cut during a short time in the meltperiod that was not detected here (ETsnow). To be able to investigate this further the observed ET should be examined more thoroughly focusing on timing and dynamics.

Since the simulated ET does not consist of the water vapour from the mechanisms sublimation and evaporation from the snowpack and the canopies (ETsnow), it is impossible to tell if a higher ETsnow could be the reason for low runoff in the CC for 2010. This is because the HBV model does not simulate the ETsnow at all, since ET is not simulated when there is snow in the model. The fact that the observed spring ET (which includes ETsnow) form Flakaliden was lower than the simulated ET for Ref means nothing since there are no observed ET datarepresenting CC.

Since there were no observed ET datafor the clear-cut area it was impossible to say if there was a higher ETsnow in CC than in Ref under the spring 2010 and if this was the explanation for the unexpected runoff behaviour. A possible difference in ETsnow between the two catchments may be due to differences in solar radiation and temperature.

So where does the water go, if there are no big variations in spring ET that can explain the low runoff in the clear-cut for 2010? According to the simulated results the soil water storage seemed to be a likely pathway for the meltwater. The change in soil water storage for CC was also positive compared to Ref which had a negative change in soil water storage for 2010, Figure 7. The difference in change between the two catchments was 28 mm, Table 6. One scenario could be that high ET in the autumn and winter in CC could lead to dry soils, leaving room for the meltwater to refill the soil water storage in CC again during the spring. To further investigate this, ET for the autumn should be examined. However, this theory is not considered likely since the soil is frequently wetter in a clear cut than in a forest. Perhaps the positive change in the soil water storage in CC for 2010 was compensation from the model since it cannot simulate the ETsnow.

Even the time when the snow starts to accumulate is important for the magnitude of the soil water storage. With an early snow accumulation the frost depth would be lower allowing more water from the spring runoff to be stored in the soil. Further analyses of any differences in frost depth between the two catchments are therefore recommended.

The precipitation during the spring period seems to have had little influence on the snowmelt. This was also considered by Schelker et al. (2013) who meant that the precipitation in the spring was so low that it did not have an effect on the snowmelt. Dry springs are also a common phenomenon in northern parts of Sweden and therefore the rain-on-snow contribution is considered insignificant (Jones and Perkins, 2010; Varhola et al., 2010b, cited in Schelker et al., 2013).

4.1.4. Comparison of simulated and observed SWE

The evaluation showed that the HBV model managed to simulate the accumulated snow quite well. However, the simulated SWE for both Ref and CC gave an underestimation compared to the measured data. A possible explanation for this behaviour is that HBV concentrates to simulate the discharge correctly and does not really care how much snow accumulates as long as it generates enough runoff. Another possible reason is that the sublimation is accounted for during the whole accumulation period in the HBV model but in reality sublimation also occurs at the end of the snow cover season before melting.

4.1.5. Comparison between simulated ET and observed ET

When comparing the simulated values of ET from Ref and CC with the observed ET from Flakaliden (Figure 12) the same pattern shown in the summary graphs (Figure 8 and 9) was exposed. The simulated values of ET were zero until the middle of May when they had values way above the observed for both 2009 and 2010. This is due to how the HBV model simulates ET. In the HBV model the simulation of ET does not start before all of the snow has melted. This means that the HBV model does not simulate the transpiration, interception and sublimation during the meltperiod. This is compensated by adjusting different parameters for example, SFCF. The instant peak spotted directly after the snow has melted (Figure 8, 9 and 12) was larger for CC than for Ref, but thereafter Ref had constantly higher values. One explanation for this could be that there was little snow on the trees compared to the accumulated snow in the open area and high radiation which leads to a higher sublimation in the CC than the Ref

The simulated values of ET followed the pattern of the observed fairly well (Figure 12) but with both under- and overestimations. However when analysing the sum of the simulated ET for Ref during the spring period with the corresponding observed values from Flakaliden the simulated values were almost a complete match for the years 2008 and 2009 (Figure 13,upper). For the other years the simulated ET was an underestimation, which was emphasised by the missing data points in the data series from Flakaliden during these years.

Looking at the annual summation of ET from Ref and Flakaliden (Figure13, lower) an overestimation for 2008 and 2007 was seen. For 2009 the simulated values still matched the observed whereas the values from 2010 still were an underestimation.

The difference in ET between the annual and the spring values indicated that it is important to study the effects seasonally as well as annually. It also indicates that it could be interesting to develop the HBV model to better simulate the ET and thereby enable better possibilities to analyse the connection between the effects of a clear-cut and ET.

4.1.6. Comparison of parameter sets between Ref and CC

The method of first calibrating the parameters for the reference area and then keeping the assumed non affected parameters within narrowed limits can be questioned. First of all the narrowed limits (95 % confidence interval) may have been to wide. The p-values for these parameters indicate this since all parameters except UZL are significantly different. The idea was to force the HBV model to use similar parameter values for these parameters to make sure that it was only the clear-cut effects that were studied. However, that insurance was gone since the supposed non affected parameter's medians varied between the two catchments.

The reason to set the limits to 95% confidence interval was that some of the parameter (UZL for both Ref and CC, as well as K1 for the Ref) distributions showed that the values were spread over a wide span, often with cluster of values close to the upper or lower limits, Figure 14. The parameter PERC and MAXBAS for CC appear to want to break free from the narrowed boundaries. This may be a way of showing that the HBV model wants to compensate for the differences between the two catchments in some other way than with the parameters that simulates the clear-cut effects. This can be seen as a confirmation that the narrowed limits were a necessity in order to establish that it was only the effects of the clear-cut that were studied. Another possibility is that the parameters assumed not to be affected by a clear-cut indeed were. In order to rule out this possibility a detailed study of the HBV model's structure has to be done.

4.1.7. Relation analysis between simulated discharge and climate parameters

As few data points (years) were available for the relation analysis, it was not possible to draw any firm conclusions. The annual analysis showed increased effect (higher runoff in CC than in Ref) as a result of less precipitation, which seemed reasonable. As the soil gets saturated less water can percolate and therefore leave as runoff. In cases with large precipitation this process will be more important, and the effect of the clear-cut on the runoff will go undetected. The clear-cut effect also increased with increased ET. Years with high ET resulted in higher runoff in CC than in Ref.

The relation analysis for the spring period did not detect any relationships. After studying both the annual and the spring analysis (Figure 15 and 16) it seemed as the years 2008 and 2010 have the same relation to each other for the same climate parameter for both the annual and the spring period. The other years (2007 and 2009) seemed to behave more random.

It is strange that an unexpected runoff behaviour (Ref had a higher runoff during the spring period than CC) was detected for 2007 in the simulated values for the spring period and not for 2010. One explanation could be that there was an earlier snowmelt period in December before the snows started accumulate again, Figure 10. This unexpected behaviour can be seen in the observed values as well but were unmentioned in Schelker et al. (2013). However 2010 did show low effect for both the annual and the spring period. This was because the year had the highest precipitation and the lowest ET which, according to the relation analysis, would result in a low or maybe negative effect.

In the relation analysis it became evident that there is a clear difference between studying the annual and the seasonal effects. In the annual study 2007 showed little effect, but for the spring the same year displayed a negative effect and thereby showed an unexpected behaviour in runoff, since a negative effect means that the runoff is higher in Ref than CC. It is strange since the year after the clear-cut generally shows a high increase in runoff. As the relation analysis gave, a possible explanation might be that there was high precipitation and low ET for that year. The year of 2007 was the year with highest annul P (Figure 15, Table 5). However, in the spring period the precipitation and SWE was not the highest for 2007 but in fact the lowest (Figure 16). Neither the annual nor the spring ET for 2007 differed from the other years.

The purpose of the relation analysis was to see if the climate can explain why different snow accumulation results in similar spring runoff some years (2010) and different runoff other years. The relation analysis indicates that the magnitude of the precipitation could affect and override some of the clear-cut effects.

4.2. Uncertainties

4.2.1. Field data

Errors in the model driving variables and calibration data have a potentially large effect on the model results, and this data uncertainty is an acknowledged problem. In this thesis interpolated precipitation and temperature from surrounding weather-stations were used, as well as PET from Svartberget and ET from Flakaliden. Nevertheless, the data used in this study were believed to be representative for Balsjö. For the SWE a more frequent amount of snow samples during the winter and spring would increase the reliability of the observed values in the future. For this study period (2007-2010) the number of samples varied between 78 and up to110. However, there were more samples taken in Ref (60-78) than in CC (32-40) (Schelker et al., 2013) which makes the SWE from CC more uncertain. The evapotranspiration, ET from Flakaliden consisted of missing values and there were several days during the observed years 2009 and 2010 where there were no data at all which questions the result of the sum of the annual and the spring period to be an underestimation. Also the nutrient applied at Flakaliden may have had an impact on the ET, and therefore make the assumption, that Flakaliden and the reference area in Balsjö can be seen as the same, invalid.

Another possibility why the unexpected runoff behavior occur for some years (2007, 2010 and 2011) may be the difficulties in measuring discharge. During the spring flood it is particularly difficult to measure, and since the difference in runoff is relatively small this possibility should be considered. For simulated values the difference in runoff between CC and Ref is 20 mm for spring 2009 and 10 mm for spring 2010. For observed runoff the difference between the two catchments was 30 mm for spring 2009 and 1 mm for spring 2010.

4.2.2. HBV model - calibration and simulation

In order to account for the uncertainties in parameter values GAP calibration was used to produce 100 calibrated and different parameter sets instead of only one parameter set. In this way the goodness of fit (weighted objective function) presented a lower value as it was measured as mean value of the 100 simulations but on the other hand the risk of a good estimation for the wrong reason was minimized.

The recommended warm-up period for the HBV model is one year and the recommended calibration period is 5-10 years (Seibert and McDonnell, 2010). This recommendation was barely fulfilled in this thesis since the calibration of Ref had six years (15-04-2005 to 31-05-2011) and the CC had five (01-03-2006 to 31-05-2011). Since there were no intention of using the calibration for simulating future predictions the result from the HBV-simulations were considered to be valid considering the available input data.

5. Conclusion

The unexpected runoff in the clear-cut area in 2010 observed by Schelker et al. (2013) could not be detected by the simulated values neither for the annual water balance nor for the spring period. The reason for this was that the HBV model was unsuccessful in distinguishing the year-to-year variations in the runoff.

Even though the simulated values did not show the same clear unusual behavior, an indication of strangely low runoff compared to the corresponding accumulated snow were observed. The reason for this was that the HBV model was unsuccessful in distinguishing the year-to-year variations in the runoff. The hypothesis that the annual variations of sublimation and evapotranspiration (ETsnow) would be the main mechanism behind the behavior of the runoff in the clear-cut catchment could neither be dismissed nor confirmed by this thesis. This was because there were no observed data for the clear-cut area and that the HBV model does not simulate ET during snow melt. This means that the sublimation and interception processes could not be analyzed.

The model results indicated that the change in soil water storage seemed to be a more likely explanation for the unexpected runoff behavior. The simulation result showed that the meltwater was stored in the soil since the change in soil water storage was positive for CC and negative for Ref during the spring of 2010. For further investigations the ET for the autumn and winter should be examined to see if it is possible that a high earlier ET can decrease the soil water storage and result in a lowered spring runoff. However, this theory does not seem likely since a clear-cut is normally wetter than a forest.

The fact that the HBV model does not simulate the ET during the snowmelt period is unfortunate. Neither magnitudes nor the dynamics of ET can thereby be studied during this period in the model. This makes it hard to determine ETs role on the spring runoff. Despite the HBV models limitations the evaluation of how the model manage to simulate accumulated snow and ET showed that the model managed well, when looking at the summation of the values for the annual and the spring period.

The relation analysis gave an indication of how the climate parameters, precipitation and ET, affected the runoff after the clear-cut in Balsjö. The annual analysis showed that a high precipitation generated a low effect (a small difference in runoff between the reference area and the clear-cut area) and a high ET resulted in a high effect.

The results of this thesis are consistent with other studies showing that increased snow accumulation and runoff as well as reduced ET are expected effects after a clear-cut. Even the suggestion that both annual and seasonal studies are needed was strengthened by this report. This conclusion originates from the clear differences in behaviour for the simulated values of ET and runoff between the annual and the spring period. The unusual element for this thesis was the opportunity to study observed ET and examine its impact on the water balance. However, neither the observed nor the simulated ET for the spring period showed an explanation for the unexpected runoff behaviour in runoff in 2010. An extended study of the seasons could clarify whether an earlier ET (autumn/winter) affected the spring flow in terms of changes in soil water storage. Also observed ET representing the clear-cut catchment is necessary to establish if a higher sublimation in the clear-cut than in the forest could be one explanation for the unexpected runoff behaviour.

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Personal communication and figures

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Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K. and Laudon, H., 2013a. Figure 1 from the article Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses, used with permission from the author.

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K. and Laudon, H., 2013b, personal communication per email with Karin Eklöf provided temperature data used in the article Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses.

Appendix

1: Another model approach

An alternative model approach would have been to put the two catchment; Ref and CC, as sub catchments in the HBV model. The reason was to enable the parameters that should be equal for both catchments (the parameters that were assumed not to be affected by a clear-cut) to be calibrated to have identical values for both catchments while the affected parameters would be calibrated separately. In this way the model is forced to think that the two catchments are one, a scenario representing something between the actual Ref and CC. This would make sure that any differences between the two catchments are a result of the clear-cut.

To make this work in the HBV model the input file (PTQ-file) had to represent data for three sub-catchments Ref, CC and one fictional. The temperature and the precipitation was the same for all three, but the runoff was specified for each sub catchment QRef, QCC and Qfictional. The fictional sub-catchment was necessary since HBV model has to link the sub-catchments to each other in some way. In this case the Ref and CC cannot be linked to each other so they were both linked to the fictional sub-catchment instead.

Unfortunately it was not possible to change and lock the parameters using GAP calibration for different sub-catchments. For Monte-Carlo calibration one could choose to have the same limits on some of the parameters for all the sub catchments, as well as different specified limits between the sub catchment. However it did not work to lock the parameters during different runs in all sub catchments. Maybe this will be a new task in the on-going development of the HBV-light model since this would be a new way of develop and insure the paired catchment studies.

2: Table of the missing values in observed ET from Flakaliden

The months marked with an x only have a few scattered data points that are missing and not a whole day. The years are not hydrological years and start from the 1st of January until the last of December.

Missing ET data	2007	2008	2009	2010	2011
Jan	x	2 days		7 days	1 day
Feb		x			
Mars		x		14 days	1day
April				11 days	4 days
May	x	8 days		1 day	
Jun					
Jul			x	x	
Aug		1 day	x		
Sep		3 days	10 days		x
Oct			10 days		
Nov		x	whole month missing	1 day	
Dec	x	2 days	whole month missing		

3: The final distribution of the different parameter sets for Ref and CC

The p-values indicates if the parameters for the reference area (Ref) and the clear-cut area (CC) are significantly separated (does not have the same median) which happens when p≤0.05. This was the case of all the parameters except for UZL and TT.

Parameter	**Ref** The distribution of the data percentiles [0.025, 0.25, 0.50, 0.75, 0.95]					**p-value**	**CC** The distribution of the data percentiles [0.025, 0.25, 0.50, 0.75, 0.95]				
Ground-water											
Perc	0.138	0.213	0.430	0.543	1.34	0.0000	0.559	1.13	1.34	1.34	1.34
UZL	6.84	8.85	64.3	85.5	99.2	0.0771	9.24	10.7	56.0	86.5	98.5
K0	0.000	0.110	0.231	0.318	0.566	0.0268	0.036	0.074	0.127	0.229	0.566
K1	0.105	0.124	0.286	0.321	0.393	0.0005	0.105	0.166	0.187	0.202	0.244
K2	0.000	0.006	0.009	0.013	0.025	0.0001	0.000	0.012	0.013	0.013	0.015
MaxBas	2.16	2.26	2.31	2.41	2.49	0.0000	2.16	2.16	2.16	2.20	2.49
Snow and soil											
TT	-0.170	0.350	0.455	0.669	1.03	0.4900	-0.210	0.310	0.451	0.494	0.964
CFMAX	1.20	1.50	1.62	1.76	2.22	0.0000	1.59	2.16	2.43	2.68	3.42
SFCF	0.636	0.674	0.697	0.722	0.772	0.0000	0.692	0.800	0.834	0.863	0.922
FC	62.0	94.1	104.4	117.2	142.1	0.0000	36.0	54.5	60.9	74.3	98.4
LP	0.592	0.779	0.899	0.962	1.00	0.0000	0.66	1.00	1.00	1.00	1.00
BETA	0.567	0.731	0.832	0.940	1.15	0.0000	0.230	0.315	0.351	0.376	0.690
weighted objective function	**0.724**	**0.730**	**0.734**	**0.750**	**0.756**	**0.0000**	**0.690**	**0.698**	**0.700**	**0.703**	**0.710**

4: Comparison of simulated and observed runoff, 2010.

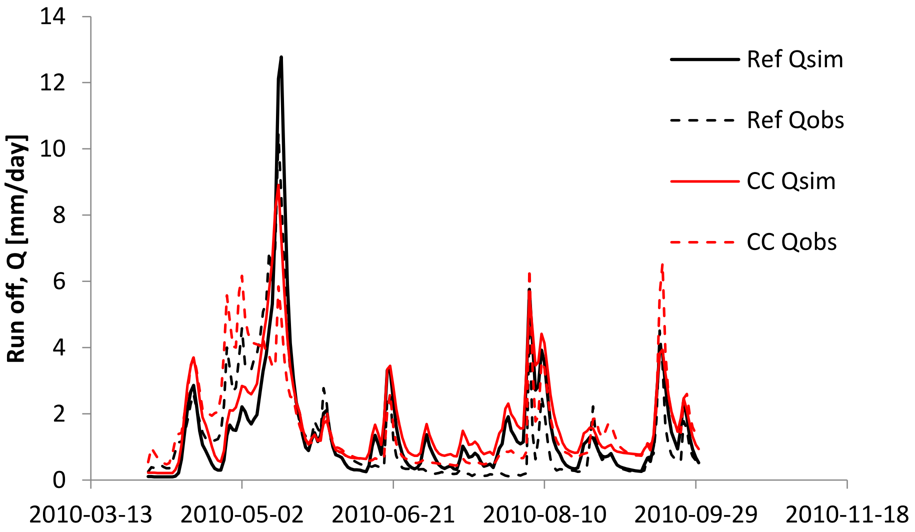

Figure 1. A comparison between simulated, Qsim and observed, Qobs runoff for the reference area (Ref) and the clear-cut area (CC) for 2010.