Examensarbeten **2010:23**
Institutionen för skogens ekologi och skötsel

The effect of forest cover for the dynamics of a snowpack

Linking snow water equivalents, meltwater contributions and evaporative loss

Álvaro Valle Millán

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Abstract

Forestry is one of the main economical activities in Sweden, but it can seriously affect the dynamic of the water cycle by altering several hydrological factors such as timing and amount of snow melt and meltwater contributions from the snowpack to the soil.

This thesis, performed during the spring 2010 within the "Balsjö Catchment Study" in Northern Sweden, was carried out in order to understand how forest cover can influence the hydrology of snow-dominated boreal catchments. The experiment was setup in two different sub-watersheds, one forested and one open (harvested by clear-cutting in 2006), within the same watershed.

Snow accumulation was found to increase 5% in the clearcut than under forest cover. Moreover, a dataset collected from different surveys carried out from 2005 to 2009 showed that snow accumulation was 20% higher in average in the open areas than forests, so that the difference between both areas in 2010 was comparably low. Snowpack reduction was faster and more constant in the clearcut, whereas the snowpack followed a more stable development in the forest, where the reduction was mostly concentrated in the last two weeks before total disappearance of snow. Meltwater contributions from the snowpack to the soil were 43% higher in the forest than the clearcut. However, calculations showed that evaporative loss from the snowpack was 44% higher in clearcut than the forested area. Therefore, the amount of meltwater released was higher (34%) than evaporative loss under canopy. The clearcut showed an opposing behavior; evaporative loss played a more important role (50% higher) than the amount of meltwater which was released.

According to the results obtained in this study, snowpack reduction and snowmelt were delayed by approximately one week in the forested area relative to the clearcut as a result of the influence of the canopy. Forest cover also increased meltwater contributions from the snowpack to the soil and decreased evaporative loss from the snowpack, playing a crucial role at controlling the water balance.

Keywords: Forest hydrology, clearcut, snow accumulation, snow water equivalents, meltwater released, evaporative loss, water balance.

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Introduction

Sweden is located in one of the few large boreal areas around the world. More than half of the Swedish land area is covered by forests and consists mainly of conifers, which represent about 85% of the total standing volume. Therefore, forest is the most important natural resource in Sweden, employing to about 100.000 people and meaning around 12% of total Swedish export income (Swedish forest agency, 2010). Thus, Logging operations represent one of the main economical activities in Scandinavia, but in general they can have a remarkable impact on the hydrology of boreal forests (Kreutzweiser et al., 2008).

However, timber production is not the only function that Swedish forest carries out. It also plays a distinguished social and environmental role. Forest also protects and affects the water cycle. Moreover, productivity and integrity are strongly linked in boreal forest ecosystems, which is simply given by the fact that the water cycle of forests connects the terrestrial and the aquatic part of the ecosystems (Buttle et al. 2005). This way, forest controls the dynamics of surface waters. It is also known that forest harvesting, can be the reason for a faster hydrological response during episodes (Jones, 2000). Without trees, snow accumulation increases, and snow melts faster in areas with a seasonal snow cover (Murray et al., 2003). This fact is supported by Musselman et al. (2008), who stated that forest vegetation can also significantly affects snow accumulation and ablation. According to Dingman (1994), snow accumulation or snowpack, was defined as the total amount of snow accumulated on the ground during a given time period, and ablation, as the total loss of water substance from the snowpack during a given time period

In snow dominated catchments, where snowmelt is often the biggest hydrological event during the year, logging operations can be the cause of flooding by accelerating the snowmelt processes during the spring, generating and excess of water that fills the streams too quickly, and resulting, therefore, in a flood. However, spring floods are nothing unusual considering that they happen regularly, and normally no damage occurs. In fact, spring floods are quite common in snow-dominated watersheds, and they are mainly caused by snow accumulation during the winter (Jost et al. 2007).

In terms of hydrology, snowmelt plays a main role in many seasonally snow covered regions (Laudon et al. 2004) being the main source of surface and ground water in many areas, and one of the main causes of flooding (Dingman 1994). The spatial variability of melt rates and peak snow water equivalent will determine the magnitude and timing of the spring snowmelt event (Jost et al. 2007).

Nevertheless, the effect of clear-cutting on snowmelt processes is not completely understood, so that the role of forests on hydrological and meteorological processes has become a “question of public interest” over the last two centuries (Andréassian, 2004).

Therefore, Sørensen et al. (2009), considers defining changes in the flow regimes, as an essential question to understand how aquatic environment is affected by forest harvesting. All this background, together with the comparably little knowledge about streamflow generation during snowmelt episodes in boreal catchments (Laudon et al. 2004), encouraged us to perform this experiment in the Balsjö catchment area. As stated by Martin et al. (2000), both forest managers and owners, must be concerned about how forest harvesting affects water quantity and quality.

The first studies on the effects of forestry on catchments started in Sweden in the early 70s. Most of these researches were focused on hydrological and biogeochemical aspects related to forests and its management (Rosen, 2009).

Different results regarding the influence of forests on the snow accumulation and snowmelt have been found by different researchers. Musselman et al. (2008) described a reduction of the snow depth and solar radiation under canopy by interception, which means a lower snow accumulation. Musselman also found that spring melt rates were higher in the open areas than under forest, delaying snow accumulation and increasing snow cover duration by minimizing snowmelt rates (Valles Caldera, New Mexico).

On the same line, Veatch et al. (2009), found that forest canopy density significantly affects snow accumulation, being higher in the forest areas than the open areas as a result of canopy interception and shading of the snowpack from direct solar radiation (Valles Caldera, New Mexico). On the other hand, Molotoch et al. (2009), described a higher snow accumulation in open areas than under-canopy places as well as a lower snow settling and ablation rates beneath forest cover, prolonging the snowmelt season in some cases (Valles Caldera, New Mexico and Niwot Ridge, Colorado).

However, these results might not be the same in boreal forests because of the big differences in climate. In boreal regions Jost et al.(2007) found that forests accumulated 39% less snow than clearcuts in 2005 and 27% less in 2006 (British Columbia, Canada). Murray and Buttle (2003) also found a higher snow accumulation and a slightly greater daily melt in the clearcut than in the forest, although the degree of difference varied with the slope and year (Turkey lakes, Ontario). Winkler et al. (2005) obtained a 32% and 14% less snow under mature and juvenile forests respectively than in the clearcut (British Columbia, Canada).

The research performed within this thesis started in April 2010 and finished in June 2010, and was carried out in the Balsjö catchment area (Northern Sweden) as a part of the “Balsjö Catchment Study”, that was initiated as a demonstration of the function of forest buffer zones within the “EU-Life project Forest for Water”.

The aim of this thesis is to determine how forest cover can influence the hydrological cycle in snow-dominated catchments by quantifying the differences in snow accumulation, snowmelt, evaporation, and water discharge into the ground. The study was performed in two different sub-watersheds, one forested, and one open (harvested by clear-cutting), belonging to the same watershed.

The hypothesized findings are an increased snow accumulation in the open area compared to forest during the first period of the snow season because of the snow interception by trees, and a faster and earlier melting of the snowpack in the open area due to a higher direct solar radiation.

Snow accumulation, evaporation rates, and the amount of meltwater released, were measured during the snow season in both areas. Timing and quantities of meltwater discharge from the snowpack to the soil were also quantified.

Materials and methods

Study area

The Balsjö catchment experiment (277 Balsjö) (64°1´53´´N, 18°55´35´´E) is situated in a boreal forest, approximately 65 km west of Umeå, in the county of Västerbotten, northern Sweden. Scots pine (*Pinus silvestris*) is the dominant species on well drained areas and Norway spruce (*Picea abies*) is the main species in wetter areas. It is also common to find some birches (*Betula sp.*) in even wetter places along the streams. The understory vegetation in the upland areas is dominated by *Vaccinium spp.*, except for small patches of *Deschampsia flexuaosa* (L.). Along the streams, understory vegetation consist of various *Sphagnum spp.* and sedges (Löfgren et al., 2009).

Mean annual air temperature is about 0,6 °C., and mean annual precipitation is 554 mm in this region. The growing season, defined as the period when the daily mean air temperature exceeds 5 ºC., lasts 150-180 days (Löfgren et al., 2009).

The bedrock is formed by pegmatite with aplite and aplitic granite, and is overlain by till (Sørensen et al., 2009). Orthic podsol is the most representative soil type in this area with histosols in wetter places (Löfgren et al., 2009). The riparian zone has often organic soils (Sørensen et al., 2009).

Within the work of this thesis, paired catchments are compared in order to assess the effects of a forest cover on the hydrological processes related to the snow as, e.g. snow accumulation, snowmelt and evaporation from the snowpack.

A control area, located in a northern control catchment (Ref-7) and a clearcut area within the clearcut catchment (CC-4) were selected for this thesis. The northern catchment is a forested area that was retained during the study, and it accounts for 23ha overall. All this area drains in the same stream. The clearcut catchment, is located downstream of the northern catchment Ref-7. It is a clearcut area and comprise of 14ha overall.

Logging operations have been performed according to recommendations in order to good practice, which include not harvesting wetlands and keeping 10 meters wide buffer riparian zones along the streams in a buffer catchment (Sørensen et al., 2009). Actual harvest percentage for site BS-5 has been estimated as 93% of the total area since there was no harvesting in wetlands and a buffer zone was retained in this site along the stream (Löfgren et al., 2009). Soilpreparation was performed as soil-scarification on harvested areas in May 2008 (Kuglerová, 2010).

Sampling, measurements and calculations

Design of the experiment

The principal idea of studying paired watersheds, is to choose two watersheds with similar properties in terms of size, geology, climate, morphology, and land use. This way, we can make sure that both areas will have a similar reaction to climatic inputs. Then, as long as the "reference" or "control" watershed will remain untreated, without having any treatment, the other one will be managed with the treatment we want to assess (Andréassian, 2004), which is, in this thesis, the forest harvesting by clear-cutting.

According to Andréassian (2004), once two basins close enough that they are exposed to the same weather conditions having a similar behavior have been chosen, the climate interference will be reduced in the design and the interpretability of the results is easier. The last requirement for a good choice is that the reference watershed should be stationary, so that the hydrological behavior during the study period can be studied.

Sampling

An intensive sampling was carried out between the 24 April and 18 May 2010 coinciding with the snowmelt period and trying to find the peaks in the snow melting. Snow depth measurements were taken every second day during this period. Before and afterwards, some snow depth measurements were taken in different days depending on the weather conditions. Meltwater contribution data were downloaded from the data-loggers (see below for a description of the experimental setup) to the computer when snow melted. The amount of meltwater released was collected by snowlysimeters and weighted in three different sampling occasions during the period specified above.

Similar to the definitions given by Dingman (1994), the terms used in this thesis are defined as the following:

"*Precipitation* is the depth of rainfall plus the water equivalent of snow, sleet, and hail falling during a given storm or measurement period"

"*Snowfall* is the incremental depth of snow and other forms of solid precipitation that accumulates on the surface during a given storm event or measurement period".

"*Snowpack* refers to the accumulated snow on the ground at a time of measurement. The snow water equivalent and areal extent are of particular hydrologic importance; information on depth and density is also useful".

"*Meltwater* is the amount of liquid water produced by melting that leaves the snowpack during a given time period; it is usually expressed as a depth".

"*Ablation* is the total loss of water substance (snowmelt plus evaporation/sublimation) from the snowpack during a given time period; it is usually expressed as a depth".

"*Snow water equivalents* (SWE), is the amount of water substance contained in the snowpack, and it is expressed as the depth of water that would result from the complete melting of the snow in place".

Snow depth measurements

In order to measure the depth of the snow accumulated in both catchments as well as its reduction by evaporation and snow melting over the time, we used a snow core. The snow core consists of a long plastic tube that is hollow inside and has a centimeter scale at the outside. The diameter of the snow core used is 4,2 cm. To observe the depth of the snowpack, it was just needed to insert the snow core through the snowpack until the ground surface, observing the height of the snowpack on the scale of the snow core. If the tube was put into the upper soil layers, the soil contained in the snow core was removed and the depth of this soil was subtracted from the snow depth measurement.

Ten snow core samples were taken randomly in both catchments every sampling day, within a radius of 30 meters from the station point established for each site. After each sample was taken, the snow accumulated inside the snow core was kept in plastic bags and weighted with a precision balance. The snow water equivalents (SWE) contained in the snowpack were calculated from the weight and depth of the snow, measured with the snow cores.

Meltwater contributions

The most common method for measuring meltwater contributions from the snowpack to the soil is by using "snowlysimeters" (Dingman, 1994). Snowlysimeters collects the meltwater draining out of the snowpack and consists of three main elements: A collector (a shower bottom), which collects meltwater from the snowpack, a plastic bag, which saves the meltwater in the collectors, and a plastic tube, which connects the collectors and the plastic bags. The tubes and the bags have to be water-tight so that no water loss occurs.

The collectors are square shaped and were installed on the ground surface before snow accumulation (October 2009), so that snow accumulated and melted in the collector similar to the surrounding ground surface. All the meltwater coming from the snowpack above the collectors is then transported to the plastic bags. The water in the bags was then quantified and some water samples were taken. The dimensions of the collectors (shower bottoms) are 80 x 80 cm in the outer part of the edge and 76 x 76 in the inner part of the edges, so that, in this study we took 78 x 78 cm as the dimensions used for calculations, assuming that half of the area of the edges drains out and the other half drains into the collectors.

The bags collecting meltwater were weighted with a balance during each sampling, determining the amount of meltwater collected (the weight of the bags -2kg- was subtracted). Further, it was needed that the plastic bags were placed below the collectors, so that the meltwater got into the bags by gravity. Collectors and plastic bags were connected by a plastic tube which was cut and fitted according the characteristics in the field.

For each sampling location (forested control and clearcut), three snowlysimeters were installed at a selected point for representing the entire area. Two of the three snowlysimeters were installed in each catchment together with the plastic bags for collecting meltwater. This meltwater were measured in three different days, representing three periods of snowmelt.

The third snowlysimeter called "tipping bucket" was installed in parallel with the others at each site (clearcut and forest). A data logger (Campbell Scientific, CR 510) was used to automatically count the amount of meltwater collected by the tipping bucket every hour.

Calculations

Snow depth measurements were used in order to calculate the amount of snow water equivalents contained in the snowpack. Snow water equivalents (SWE), were defined as the volume of water per unit area (formula 1), that would result from the complete melting of the snow in place, so

$$SWE = \frac{Vs}{A} \quad \left[\frac{dm^3}{m^2}\right] = \left[\frac{l}{m^2}\right] = \lfloor mm \rfloor \qquad (1)$$

Snowpack reduction was estimated as the difference of SWE in the snowpack between two measurements taken in a row. It was expressed as a water volume in mm.

Regarding to the results obtained for meltwater released by the snowlysimeters, the seemed to be slightly delayed probably as a result of ice formation in the plastic tubes draining the collectors. Therefore a correction of meltwater data was performed for the three different periods in order to calculate the evaporative loss as accurate as possible.

The correction consisted of dividing the values obtained as snowpack reduction for each period by a factor (2,30) which was estimated by dividing the sum of snowpack reduction by the sum of meltwater released during the three periods. Then the results were expressed as meltwater correction or “meltwater normalized” and their units kept being mm. This way, negative values in evaporative loss calculations were avoided by suppressing the delay caused by the ice. For the rest of the calculations, the uncorrected values of meltwater released were taken considering the delay produced by ice as a part of the meltwater dynamic.

Finally, evaporative loss was estimated as the difference between ablation (calculated as snowpack reduction by comparing differences in SWE between different measurements) and meltwater released (after corrections) in the snowlysimeters during the same time period. It was expressed as a water volume in mm.

Large scale comparison

To get a long term perspective of the result obtained during this study in 2010, snow accumulation data was collected from different snow surveys carried out between 2005 and 2009 in the open and the forested area. This data represent the annual variability regarding total snow accumulation in each site.

A comparison between open and forested areas was performed for every single year in order to assess the differences in total snow accumulation and obtaining a large scale view.

Open areas existed in the large scale dataset even before cutting. This data comes from mires, naturally open areas.

Results

Snowpack development

The figure below (Figure 1) shows the snowpack development over the time and compares the difference between the open and the forested area. Snow accumulation was higher in the open area from February to mid April 2010. The forested area kept higher values afterwards, until the snowpack was completely melted. The highest value for both areas was 192 mm (Table 1) and was reached in April in the clearcut.

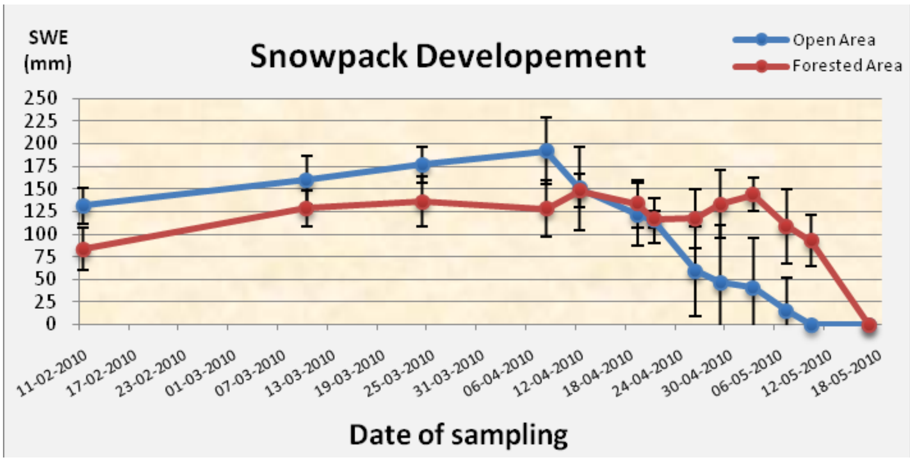

Figure 1. Snowpack development expressed as SWE (Snow water equivalents or amount of water substance contained in the snowpack and expressed as the depth of water that would result from the complete melting of the snow in place) in mm for the forested and the open area in Balsjö.

Snowpack reduction remained quite low in both areas until mid April (Figure 2). From mid April on, it started to increase in both areas, and was always higher in the open area, reaching the total snowpack reduction at the end of the melting period in mid May, which accounted for 192 mm. Forested area total reduction was 182 mm (Table 1).

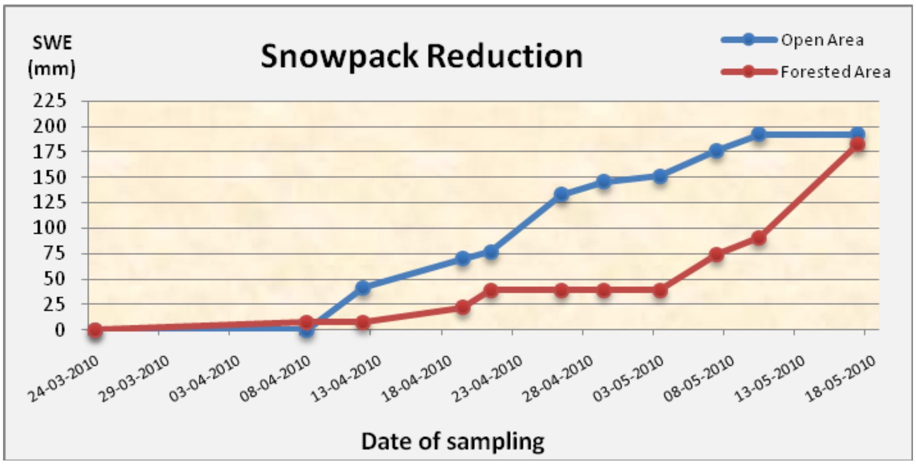

Figure 2. Cumulative snowpack reduction (sum of the differences between the average snow accumulation measured every sampling day "n" minus the average snow accumulation measured the sampling day before "n-1") expressed as SWE in mm for the forested and the open area in Balsjö.

Different values obtained for snow accumulation are shown in Table 1 as the average between all the measurements taken in the field every sampling day. Standard deviation (STD) is shown together with the average value. Snow accumulation measurements are expressed as snow water equivalents (SWE) in mm.

Table 1. Average snow accumulation for every sampling day expressed as SWE in mm together with their standard deviation (STD) and cumulative snowpack reduction (sum of the differences between the average snow accumulation measured every sampling day "n" minus the average snow accumulation measured the sampling day before "n-1") expressed as SWE in mm.

SNOWCORES 2010 SUMMARY						
	Open Area			Forested Area		
Date of Sampling	Snow Accumulation SWE (mm)	STD	Cumulative Snowpack Reduction SWE (mm)	Snow Accumulation SWE (mm)	STD	Cumulative Snowpack Reduction SWE (mm)
11/02/2010	131,62	19,66	0,00	83,39	23,51	0,00
10/03/2010	160,14	26,85	0,00	128,74	20,00	0,00
24/03/2010	177,11	19,70	0,00	135,96	27,55	0,00
08/04/2010	192,06	36,52	0,00	128,38	31,37	7,58
12/04/2010	150,40	46,49	41,66	148,16	18,65	7,58
19/04/2010	121,88	34,21	70,18	133,72	26,53	22,02
21/04/2010	115,02	24,62	77,04	116,46	9,39	39,28
26/04/2010	59,03	49,50	133,03	117,55	32,55	39,28
29/04/2010	46,50	63,38	145,56	133,00	37,89	39,28
03/05/2010	40,72	55,04	151,34	143,68	18,68	39,28
07/05/2010	15,42	35,94	176,64	108,88	40,77	74,08
10/05/2010	0,00	0,00	192,06	92,56	28,42	90,40
17/05/2010	0,00	0,00	192,06	0,00	0,00	182,96

Snowpack reduction, meltwater released and evaporative loss

Highest snowpack reduction occurred during the first time period (from 11/02/2010 to 21/4/2010) in the open area, with values close to 80 mm and then, it decreased during the two following periods according to Figure 3. Evaporative loss followed the same trend, reaching around 44 mm in the first period and decreasing afterwards. With regards to meltwater released, the peak was reached in the second period (from 21/4/2010 to 26/4/2010) accounting for a bit more than 41 mm collected.

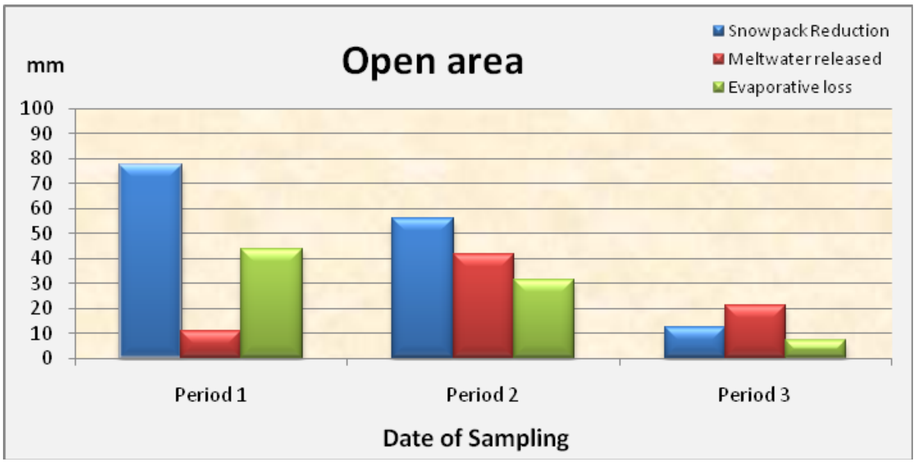

Figure 3. Comparison between snowpack reduction measured as SWE in mm, meltwater released measured in mm and evaporative loss measured as SWE in mm for three different periods in the open area. Period 1: from 11/02/2010 to 21/4/2010; Period 2: from 21/4/2010 to 26/4/2010; and Period 3: from 26/4/2010 to 29/4/2010.

Very different results were obtained in the forested area though. The graph below (Figure 4) shows the second period (from 21/4/2010 to 26/4/2010) as the one with highest values. Snowpack reduction and meltwater released accounted for about 92 mm during this period, whereas evaporative loss was much lower accounting for 23 mm. No snowpack reduction and evaporative loss was calculated during the third period (from 14/5/2010 to 17/5/2010), where only a small amount of meltwater was collected.

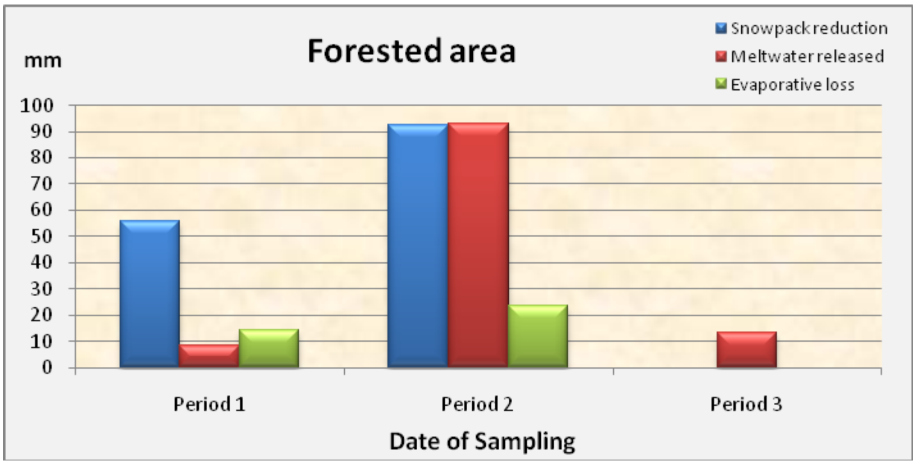

Figure 4. Comparison between snowpack reduction measured as SWE in mm, meltwater released measured in mm and evaporative loss measured as SWE in mm for three different periods in the forested area. Period 1: from 11/02/2010 to 10/5/2010; Period 2: from 10/5/2010 to 14/5/2010; and Period 3: from 14/5/2010 to 17/5/2010.

A continuous increment of meltwater released was observed from Period 1 to Period 3 in the open area (Figure 5). More than 80% (44 mm) of the ablation corresponded to evaporative loss in Period 1, whereas meltwater released accounted for a bit less than 20% (11 mm). However, a different situation was founded in Period 3, where more than 70% (21 mm) of the ablation was meltwater released, whereas evaporative loss accounted for less than 30% (7 mm).

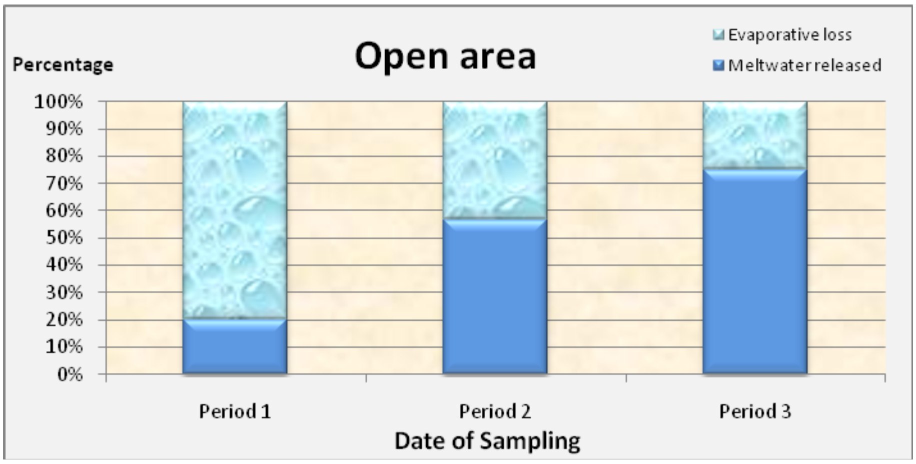

Figure 5. Percent comparison between evaporative loss, measured as SWE in mm, and meltwater released measured in mm in the open area. Period 1: from 11/02/2010 to 21/4/2010; Period 2: from 21/4/2010 to 26/4/2010; and Period 3: from 26/4/2010 to 29/4/2010.

A similar situation as shown above is given by Figure 6 for the forested area. The behavior was rather similar to the open area, but meltwater rates were clearly higher and evaporation rates clearly lower. Almost 40% (8 mm) of the ablation in Period 1 and 80% (93 mm) in Period 2 appeared as meltwater released. Evaporative loss was more than 40% (14 mm) of the total ablation in Period 1 and 20 % (24 mm) in Period 2. No evaporation was calculated in Period 3.

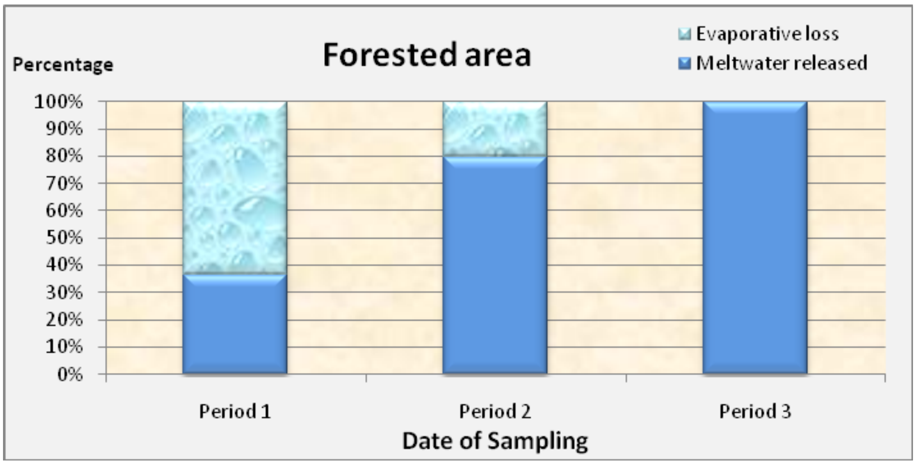

Figure 6. Percent comparison between evaporative loss measured as SWE in mm and meltwater released measured in mm in the forested area. Period 1: from 11/02/2010 to 10/5/2010; Period 2: from 10/5/2010 to 14/5/2010; and Period 3: from 14/5/2010 to 17/5/2010.

An overview of all measurements and calculations carried out for each variable in each period as well as the sum of the three periods is shown in Table 2, including snowpack reduction, meltwater released, and evaporative loss. A correction of meltwater released, performed in order to avoid the delay produced by ice formation when collecting meltwater by snowlysimeters, is also shown as “meltwater normalized”. Correction method has been described in “material and method”.

Table 2. Snowpack reduction expressed as SWE in mm, meltwater released expressed in mm, meltwater normalized (meltwater released corrected by dividing it by a calculated factor as explained in “material and methods”) expressed in mm and evaporative loss expressed as SWE in mm, measured for the open and the forested areas in three different periods. Periods range for the open area; Period 1: from 11/02/2010 to 21/4/2010; Period 2: from 21/4/2010 to 26/4/2010; and Period 3: from 26/4/2010 to 29/4/2010. Periods range for the forested area; Period 1: from 11/02/2010 to 10/5/2010; Period 2: from 10/5/2010 to 14/5/2010; and Period 3: from 14/5/2010 to 17/5/2010.

		OPEN AREA		
Date	Snowpack reduction (mm)	Meltwater released (mm)	Meltwater normalized (mm)	Evaporative loss (mm)
Period 1	77,04	11,09	33,49	43,55
Period 2	55,99	41,50	24,34	31,65
Period 3	12,53	21,37	5,45	7,09
Sum	145,56	63,28	63,28	82,28
		FORESTED AREA		
Period 1	55,60	8,22	41,35	14,24

Period 2	92,56	92,87	68,85	23,71
Period 3	0	13,23	0,00	0,00
Sum	148,16	110,21	110,21	37,95

Total loss of water substance

Total loss of water substance from the snowpack expressed as meltwater released and evaporative loss for the entire sampling period (from the beginning of the experiment until complete disappearance of snow) are compared for the two studied areas.

Total values of snowpack reduction, meltwater released and evaporative loss are represented in Figure 7. Meltwater released (63 mm) was remarkable lower than evaporative loss (129 mm) in the open area. However, an opposing situation was found in the forested area, where meltwater contributions were higher (over 110 mm released) than evaporative loss (almost 73 mm). Snowpack reduction was very similar in both areas, ranging from 182 mm (forested) to 192 mm (open).

Comparing both sites, meltwater released was higher in the forested area (110 mm) than the open area (63 mm). However, evaporative loss was almost two times higher in the open area (129 mm) than the forested area (73 mm).

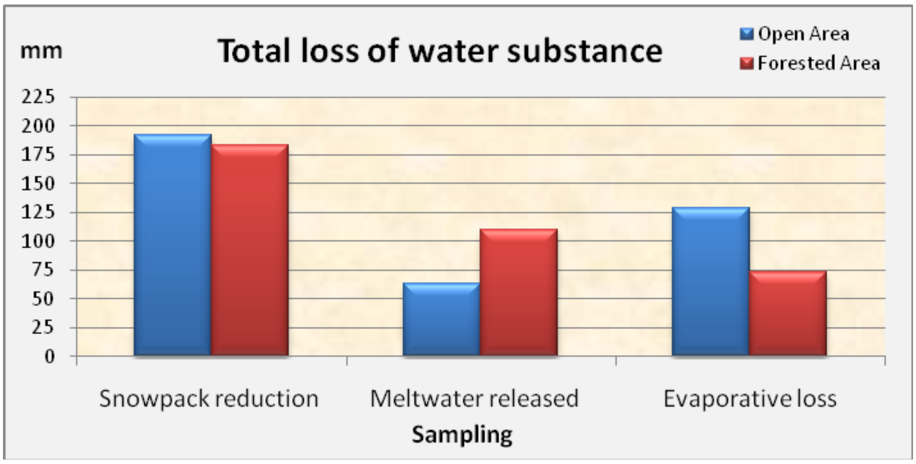

Figure 7. Total loss of water substance expressed as snowpack reduction measured as SWE in mm, meltwater released measured in mm, and evaporative loss measured as SWE in mm in both areas.

Total evaporation ratio of the total ablation was clearly higher in the open area than the forest (Figure 8). Evaporative loss accounted for 129 mm in the open area, a bit less than 68% of the total ablation, whereas it accounted for 73 mm, around 40% of the total ablation, in the forested area. Therefore, the amount of meltwater released was higher in the forested area than the clearcut.

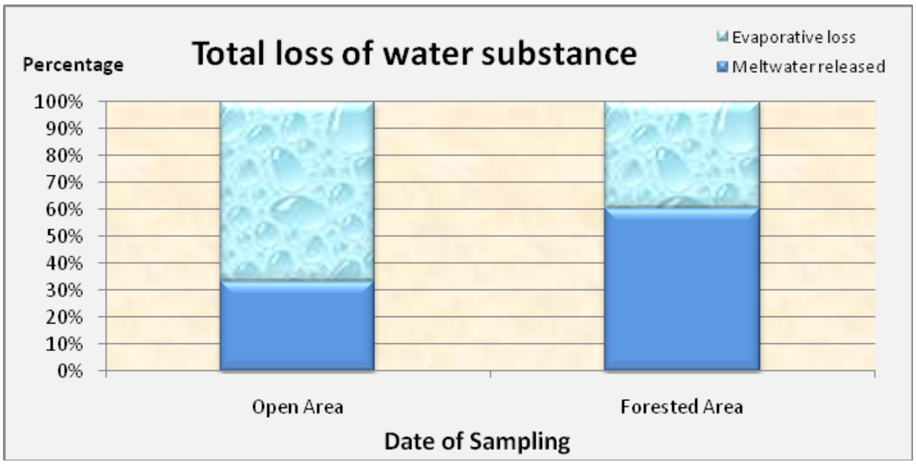

Figure 8. Percent comparison between evaporative loss measured as SWE in mm and meltwater released measured in mm for both, the open and the forested area.

Total loss of water substance from the snowpack is shown below (Table 3) divided in snowpack reduction, meltwater contributions and evaporative loss for each area.

Table 3. Total loss of water substance divided in snowpack reduction measured as SWE in mm, meltwater released measured in mm, and evaporative loss measured as SWE in mm.

TOTAL LOSS OF WATER SUBSTANCE			
Site	**Snowpack reduction (mm)**	**Meltwater released (mm)**	**Evaporative loss (mm)**
Open Area	192,06	63,28	128,78
Forested Area	182,96	110,21	72,75

Large scale snow accumulation

Annual variability in total snow accumulation from 2005 to 2010 is shown in Figure 9. Total snow accumulation was always higher in the open area than the forest, and the difference varied with the year. Open area values ranged from 190 to 350 mm whereas forested area ranged from 135 to 280 mm of total snowfall accumulated. The higher value for both areas was registered in 2008 with 349 and 278 mm of snow respectively, and the lower one took place during 2007 with 188 and 139 mm.

Snow accumulation was very similar between the years 2006, 2007 and 2010. However, during this study in 2010, the snow accumulation was unusually close between the open and the forested area compared to the rest of the years.

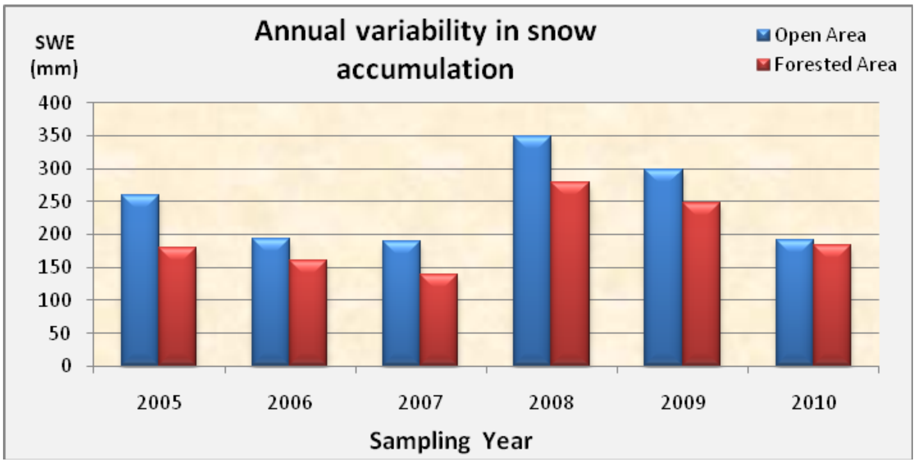

Figure 9. Annual variability in total snow accumulation from 2005 to 2010 expressed as SWE in mm.

Average snow accumulation (between the six years) in the clearcut was 247 mm, whereas it was 198 mm in the forested area (Table 4). Average difference between both areas was about 50 mm, which means that on average, the forest accumulated 20% less snow than the open area.

This percentage varied between years, being 31% less snow in the forest in 2005 as maximum difference, and 5% less snow in 2010 as minimum difference. However, even though the difference tended to decrease through the years, it is obvious that the forested area accumulated less snow than the clearcut every year.

Table 4. Annual variability in total snow accumulation from 2005 to 2010 expressed as SWE in mm. Differences (in mm) and the reduction percent between open and forested areas are shown for every year.

Annual variability in total snow accumulation				
Sampling Year	**Open Area (mm)**	**Forested Area (mm)**	**Difference (mm)**	**Reduction (%)**
2005	260,09	179,93	80,16	31
2006	192,48	159,67	32,81	17
2007	188,91	139,64	49,26	26
2008	349,43	278,70	70,74	20
2009	297,66	248,41	49,25	17
2010	192,06	182,96	9,10	5
Average	246,77	198,22	48,55	19

Discussion

Problems and limitations

Some limitations during sampling and calculations must be considered. One major problem regarding to meltwater measurements was a delay produced when collecting meltwater from the snowpack, probably caused by ice formation in the outlets of the snowlysimeters or the tubes draining the lysimeters, which both could have blocked and delayed the meltwater draining into the collector bags.

This delay caused by ice, was considered as a normal process before meltwater infiltration into the ground, so that no correction was applied to the dataset of released meltwater. However, this delay caused a problem when calculating evaporative loss as the difference between snowpack reduction between two snow core samplings, and meltwater contributions collected by snowlysimeters, since the snowpack reduction did not have any delay, so that some negatives values for evaporative loss were calculated. Therefore, correction of the meltwater data had to be applied for the three different periods in order to calculate the evaporative loss as accurate as possible. The correction consisted of dividing the values obtained as snowpack reduction for each time period by a factor (2,30) calculated by dividing the sum of snowpack reduction by the sum of meltwater released during the three periods. These results were expressed as "meltwater normalized". This way, negative values in evaporative loss calculations were avoided by suppressing the delay produced when collecting meltwater. For the rest of the calculations, the original values of meltwater released were taken, considering the delay produced by ice as part of the meltwater dynamic. This correction involved an error in the results of evaporative loss, which was not taken into account considering that it was small enough for not influencing the overall results.

Another problem which came up during sampling drawing was the uneven snowpack surface, which supposed an error when collecting snow depth and density data by measurements with the snow core because of the high depth variability. Ten snow core samples were taken every sampling day around each site point in order to quantify the variation of SWE by calculating average values and standard deviations.

Another critical point of the data collection was the use of a tipping bucket attached to the third snowlysimeters at each site. Even if the tipping bucket was calibrated with a known amount of water beforehand in the laboratory, the measurement unit quantified only a small part of the water collected in the collector bags during the same time periods. This loss of meltwater could have been caused by leakage or by simple overflow of the tipping buckets, when the meltwater contribution was large (in the range of several liters/hours), which occurred during peak melting periods. Therefore the results from the tipping buckets are questionable and were excluded from the data presented in this thesis.

Snowpack development

Total snow accumulation in Balsjö for the entire period was 5% higher in the open area (192 mm) than in the forest (182 mm). This result corresponds to other results given in boreal regions, although other researchers found that snow accumulation in open areas was even higher than 5% compared to forests. Jost et al. (2007) found that forests accumulated 39% less snow than clearcuts in 2005 and 27% less snow in 2006 in a research carried out in British Columbia (Canada). Similarly, Winkler et al. (2005) obtained a 32% and 14% less snow under mature and juvenile forests respectively than in the clearcut in the same region (British Columbia). Alike, a higher snow accumulation and a slightly greater daily melt was also found by Murray and Buttle (2002) in the clearcut compared to the forest in the Turkey lakes (Ontario), although the degree of difference varied with the slope and year.

The fact that the difference in snow accumulation between forested and open areas found in Balsjö was lower than the differences found in other boreal regions, could be explained considering the unusual climate during the study period in Balsjö (2010). Continuous frost during the nights together with clear and sunny days, increased evaporation rates specially in open areas, where no shadow protects the snowpack from direct solar radiation. Thus, snowpack reduction could be unusually higher in open areas than forests, causing snow accumulation remain low, and reducing the differences in snowpack accumulation between both areas. This fact can be observed by comparing the average total snow accumulation from 2005 to 2009 (247 mm), to total snow accumulation in 2010 (192mm) in the open areas. There was a remarkable difference, whereas there was not such a big difference if we compare the average total snow accumulation from 2005 to 2009 (198 mm), to total snow accumulation in 2010 (182 mm) in the forested areas. In addition, there was almost no rain on snow (ROS) in 2010, whereas in many other years peak melt is often caused by one or more rain on snow events.

Some other different results have also been found in different regions than boreal areas. Musselman et al. (2008) describes a 47% less snow accumulation at maximum under canopy than open areas in Valles Caldera (New Mexico). However Veatch et al. (2009) found that forest cover significantly affects snow accumulation, being 7% higher in forest than open areas in the same place (Valles Caldera). Molotoch et al. (2009), found a 29% higher snow accumulation in open areas than under forest cover in Valles Caldera (New Mexico) and Niwot Ridge (Colorado).

It could be therefore, that the snowmelt investigated in this study was more similar to a behavior found in warmer climatic regions with high elevation (Musselman et al., 2008; Veatch et al., 2009; Molotch et al., 2009), where evaporative loss from the snowpack is much higher and the amount of meltwater infiltration into the soil is lower, than boreal regions, and that the snowmelt 2010 in Balsjö was mainly dependent on solar radiation, which is not the major driver of snowmelt during most years (often rain on snow events occur as well).

This study also showed a more stable snowpack development in the forest than the open area. The snowpack grew continuously from the beginning of February in the open area, reaching a peak in the beginning of April that accounted to 192 mm as the highest value. From this peak, the snowpack started to decrease rapidly until total snowpack disappearance, which took place the first week of May. A different situation was found in the forest, where the snowpack described a really stable trend from February to the beginning of May. During this time, it was growing slowly, reaching a couple of peak points (12nd April, 3rd May) which accounted around 150 mm. Then, it started to decrease, disappearing definitely in mid May. A lower average standard deviation (24,25) was calculated in the forested area than the clearcut (31,69) for the snowpack measurements, what also suggests a lower snowpack variation in the forest than the clearcut.

This more stable situation in the forested area can be explained as a result of snow interception and protection of direct solar radiation by forest cover. From February to mid April, the forested area always presented lower values of snowpack accumulation than clearcut, probably because of snow interception by forest, which reduced the snow accumulation on the ground. Nevertheless, from mid April on, lower snowpack accumulation levels were founded in the clearcut. It is probably the result of a higher snowmelt and evaporation rates which reduced the snowpack constantly, whereas the forested area was protected from direct solar radiation by the dense canopy, maintaining lower evaporation rates than the clearcut and delaying the reduction of the snowpack. Therefore, the reduction of the snowpack was mostly concentrated in the last two weeks (from 3rd May to 17th May) before total snowpack disappearance in the forested area, whereas it was more constant in the clearcut, starting the 8th of April and finally disappearing entirely on the 10th of May. Thus, canopy protection from direct solar radiation resulted in a lower evaporation rate, which delayed the final disappearance of the snowpack by approximately one week.

Meltwater released and evaporative loss

Forest cover had a clear influence on the amount of meltwater released from the snowpack to the soil. Evaporative loss was also clearly influenced by the canopy. In the clearcut, total evaporative loss was 44 % higher than the forested area as a result of direct solar radiation. Total evaporative loss was also 50% higher than meltwater released in the clearcut, what means that evaporation was the major fraction for the reduction of the snowpack in the open area during the snowmelt event in 2010.

The forest, where the amount of meltwater released was 34% higher than evaporative loss, followed and opposing behavior. Meltwater represented the main cause of reduction of snowpack in this area. Forest cover controlled evaporation rate, keeping it low in comparison to the clearcut, and allowing a higher snowmelt from the snowpack. Further, the amount of meltwater released was 43% higher in the forest than the open area, providing a greater amount of meltwater infiltrating into the soil and potentially discharging into the streams.

Total evaporation ratio was higher in the open area than the forest, meaning 68% of the total ablation (the remaining 32% was meltwater), whereas in the forest, evaporation accounted for 40% of the total ablation (60% was meltwater). Meltwater contributions from the snowpack to the soil increased constantly from February to May in both areas as a result of the higher temperatures. Similarly, evaporation loss was proportionally decreasing during this period. However, even though the trend in both areas was the same, there was a delay in the forested area, where melting period and changes in evaporation and meltwater rates started between one and two weeks later than the open area.

Conclusion

The data shown in this thesis for the Balsjö catchment show that forest coverage can clearly influence the dynamics of the snowpack by changing meltwater contributions from the snowpack to the soil and altering evaporation rates from the snowpack. These results are also supported by literature where similar studies were carried out in boreal areas (Jost et al., 2007; Winkler et al., 2005; Murray and Buttle, 2002).

Forest cover decreased snow accumulation in Balsjö study site in 2010, being 5% higher in the clearcut than the forested area. Further, a dataset from previous years showed that snow accumulation was always higher in the open areas from 2005 to 2009, accounting for an average increment of 20% more snow in the clearcuts compared to the forests. Moreover, snowpack development was more stable in the forest, where snowpack reduction was mostly concentrated in the last two weeks before total snow disappearance, and therefore, snowmelt was faster and more constant in the clearcut. Snowmelt processes and snowpack reduction were delayed in the forest probably as a result of the canopy, lasting around one week more than in the open area.

This study also showed that meltwater contributions from the snowpack to the soil increased by 43% in the forested area compared to the clearcut, whereas evaporative loss from the snowpack were 44% higher in the clearcut than the forest. Therefore, evaporative loss was higher (50%) than meltwater released in the clearcut, whereas the opposite situation occurred under canopy, where meltwater released was 34% higher than evaporative loss.

Summarizing, forest cover resulted in a relevant factor for the water balance. Meltwater contribution from the snowpack to the soil increased and evaporative loss from the snowpack decreased in the forested area compared to the clearcut. Forest cover also delayed snowmelt processes and snowpack total disappearance and decreased snowpack accumulation.

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