Effects of Forest Harvesting on the Hydrology of Boreal Streams

The Importance of Vegetation for the Water Balance of a Boreal Forest

Photo: Jakob Schelker

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Nyckelord / *Keywords:*

Water balance, clear cutting, forestry, runoff dynamic, evapotranspiration, snow accumulation.

Abstract

Forestry is one of the main industries in Scandinavia but also timber harvesting can have a large impact on the ecology and hydrology of boreal forests. The removal of the forest canopy alters many variables in the catchments such a snow accumulation, timing of the snow melt, evapotranspiration, interception loses and soil characteristics. All these factors result in changes in the dynamic of streams draining operational forests.

This thesis reports on the changes in the stream regimes during a three year period after forest harvesting, performed in March 2006, at the Balsjö Catchment study in Northern Sweden. To quantify the effect of harvesting the different variable of the water balance equation were investigated by comparing the harvested and the reference catchments. The experiment is set up as a paired catchment study so that the observed changes can be reported relative to the reference area and to the pre-harvesting period which includes 18 months before forest harvesting (September 2004 - March 2006).

After the forest harvesting the runoff increased approximately 30% in average at the two harvested sites relative to the reference. The number of days with low flows (<1mm/day) decreased about 20% after harvest for all harvested studied sites, the days with moderate (1-5mm/day) flow increased more than 60%, relative to the reference site. The peak events responded the strongest at the reference catchment before clear cutting. After forest removal almost all peak flows were observed to be highest at the harvested sites. The annual evapotranspiration quantified by the water balance approach decreased from 286 mm in 2005 to 167 mm in 2006 and 151 mm in 2007 at the harvested site, whereas it increased in 2008 again, possibly due to the re-growth ground vegetation. The snow accumulation was higher at the open areas in comparison to the forest resulting in a difference in snow depth of about 8-18 cm which accounts for a difference in the snow water equivalent (SWE) between 30 and 80 mm.

These results suggest that forest harvesting strongly affects the water balance of a catchment. The higher runoff is mainly caused by lower evapotranspiration during the growing season as well as higher snow accumulation and therefore melted water contributions during the winter season.

Keywords: water balance, clear cutting, forestry, runoff dynamic, evapotranspiration, snow accumulation.

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Introduction

Forest covers approximately 60% of Sweden's almost 27 million ha. The dominant type is considered being boreal forests (Swedish forest agency 2009). Over the centuries these forests have played an important ecological, economical, social and cultural role at the local, regional and global scale. Forest hydrology is therefore unique regarding to processes affecting the water cycle and has attracted a lot of attention in the past (Buttle et al., 2005). Increasing knowledge about hydrological processes in forests is the way how to accurately predict and manage consequences of forest disturbance. Forest managers, owners and loggers need to be concerned about the effects of harvesting operations on stream water quantity and quality (Martin et al., 2000). Therefore, forest hydrology and ecology should be considered together because linkages between terrestrial and aquatic systems influence ecosystem productivity and integrity (Buttle et al., 2005).

Harvesting of timber is one of the main industries in Scandinavia but similar to a change in land use it can have a large impact on the ecology and hydrology of boreal forests. In high latitude regions logging disturbances as e.g. soil preparation techniques can alter biochemical process in soils by changing forest composition, plant uptake rates, soil condition and temperature regimes, soil microbial activity, and water fluxes (Kreutzweiser et al., 2008). "The runoff from forested land is a function of precipitation, evapotranspiration and the water storage capacity of the soil" (Rosén 1984). Therefore, changes in stream runoff can be expected as a response to forest harvesting. Cutting of timber results in (1) decreasing evapotranspiration rates and changes in the water balance of the watershed; (2) greater accumulation of snow in open, clear-cut areas compared to the closed forest; and (3) changes in rainfall interception, throughfall and infiltration rates (Sørensen et al., 2009; Troendle & Stednick 1999). Hence, total runoff and peak flows generally increase with forest disturbance (Buttle et al., 2005; Corner et al. 1996; Sørensen et al., 2009) and the water balance is implicitly changed to comparison to forested areas. However, several studies illustrate changes in runoff after forest harvesting but only a few studies exist, which investigate the changes under Swedish conditions (Rosén 1984; Sørensen et al., 2009).

The results of studies focusing on stream responses after timber harvesting in the literature differ. Robinson et al. (2003) and Martin et al. (2000) indicate that complete clear felling can increase peak flows. Buttle & Metcalf (2000) did not observe significant changes in runoff/precipitation ratios and peak flows for larger basins (Ontario, Canada) and Meng et al. (1995) found only small effects of harvesting on forest hydrology in the Nashwaak Experimental watershed (New Brunswick, Canada). Sørensen et al. (2009) found increases in runoff from harvested areas but no evidence for increases in peak flows in northern Sweden. The importance of local conditions is therefore fundamental and differences in annual meteorological data are similarly relevant as the differences of harvesting timing and technique.

Evaporation, transpiration and interception losses are important elements of the water balance equation, especially during the summer. "Evapotranspiration is the sum of the volume of water used by vegetation (transpired), evaporated from the soil and the intercepted precipitation on vegetation" (Kisi 2007) and it is the dominant process regulating water balance in forested areas (Jutras et al., 2006). Therefore, a decrease of the vegetation cover plays the key role in the changes of the hydrological balance. The big effect can be noticeable during the small storms when nearly all rain may be intercepted and lost by the forest but not

by the grass cover (Moore & Wondzell 2005). Further, "forest covers receive larger amounts of energy because of its smaller albedo compared to croplands, grassland, and bare soils. Therefore, forest evapotranspiration is generally found to be larger than that of other vegetation types such as grassland." (Matsumoto et al., 2008)

The eddy covariance technique is probably the most common method to measure forest evapotranspiration directly but it was shown that this direct measurement has limitations (Amiro 2001). Estimation of actual ET without using flux towers becomes more difficult. During last decades many ET models based on different meteorological parameters were established (e.g. Penman-Monteith, Turc, Thornwhite, Blainy-Cridle) but those still just provide potential estimates (Oudin et al., 2004). The definition of "potential evapotranspiration" is formulated as a "rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water, and without advection or heat storage effects" (Dingman 2000). Hence, the cutting of timber which causes a dramatic loss of vegetation cover is crucial for changes of the evapotranspiration rate. This is especially important if the conditions for potential evapotranspiration are barely fulfilled.

In this thesis I provide the annual differences in runoff of a clear cut compared to a forested reference site in northern Sweden as were studies in the 277 Balsjö experiment. The experiment started in September 2004 and the forest harvest was performed in March 2006. Therefore, this thesis presents the results from the pre-harvest and the post-harvest period (until October 2009) and shows the relationship between harvested and reference sites. I investigate the relationship between precipitation and specific discharge. How streams responded on the different events (rain, snow melt) are compared and the discussed. Furthermore, the changes in the hydrological balance of the forested and treated watersheds were investigated. I estimated the evapotranspiration rates at the study sites with the different vegetation cover using three different approaches. Further the snow accumulation on the different sites was measured and snow water equivalent was calculated for open and forested areas. This study can be partly seen as a follow up on the work done by the Sørensen et al. (2009) but with a main focus on the water balance.

Materials and methods

Study area

The study site, 277 Balsjö (64°1´53´´N, 18°55´35´´E) is situated approximately 70 km west from Umeå, Västerbotten län in northern Sweden. The four catchments are situated in the boreal coniferous forest zone, which is typical for northern Sweden. Species composition is dominated by Scots pine (*Pinus silvestris*) and Norwegian spruce (*Picea picea*) in moister areas some birches (*Betula* sp.) can be found. The vegetation in the upland is dominated by *Vaccinium* spp., except for small patches of *Deschampsia flexuaosa* (L.). Along the streams various *Sphagnum* spp. and sedges dominate (Löfgren et al., 2009).

"Mean annual precipitation in the region is 554 mm, with mean temperature of 0,6° C. The bedrock consists of pegmatite with aplitic granite and aplite and is overlain by till" (Sørensen et al., 2009). "The dominant soil type in the area is orthic podsol with histosols in wetter areas" (Löfgren et al., 2009).

Similar to most other studies focusing on the effect of forest harvesting (e.g. Buttle & Metcalfe 2000; Meng at al., 1995; Sørensen et al., 2009) this study is set up as a comparison of harvested and control sites using a paired catchment approach. In this thesis three catchments with different treatments were compared. The two northern catchments are situated next to each other and account for a total area of 37 ha. The entire area was forested until March 2006 and is drained by the same stream. 68% (23 ha) of the northern area were retained as a forest and are considered to be the reference area (Ref-7) for this study. Downstream of the reference site the clear cut site (BS-5) is situated and which represents a 14 ha area with a riparian buffer strip along the stream. The buffer zone is approximately 5-10 m wide to each side. The third area (CC-4) is located 2 km south of the northern catchment, is entirely clear cut. In this 45 ha catchment no buffer zone was left.

Catchment areas were defined using Digital Elevation Models with flow algorithms. Additionally a mapping of the areas of low relief often with flow directions provided by small ditches was conducted directly in the field. Additionally the mapping was supported by air photographs and an experienced cartographer in the field (Sørensen et al., 2009). Due to ongoing field measurements the areas of the catchments were updated several times during the study period. In this thesis the newest areas determined in October 2009 are used.

The clear cut areas (BS-5 and CC-4) were harvested in March 2006 with standard practice. During the harvesting there was more than 1 m of snow, areas dominated by wetlands and small rocks were not harvested. The machinery stayed out of the near steam zone (at least 10 m from the stream). At site CC-4 the machinery had to cross the stream at two places with using logs set up as a temporary bridge. Since wetlands were no harvested and the buffer zone was left at site BS-5 the actual percentage of harvest on the site BS-5 is given with 93% and for site CC-4 73%. (Löfgren et al., 2009; Sørensen et al., 2009). Additionally soil preparation was performed on harvested areas in May 2008. The scarification was done using a disc trencher with approximately 2 m between each furrow (Lars Högbom, Skogforsk, November, 2009 personal communication).

Specific discharge

During summer 2004 90° V-notch weirs were installed at streams draining the study sites for measuring runoff from each catchment. At each weir water level measurements were performed in 15 minute interval using two different types of loggers (TrueTrac and Campbell Scientific). Data were averaged to daily values and used for calculation of runoff. The measurement started in July 2004 at site CC-4. All other sites were in operation by September 2004 (Sørensen et al., 2009).

This study reports flows from September 1, 2004 to October 31, 2009 expressed as specific discharge which gives the means volume rate of flow per unit area (Dingman 2002). Due to the fact that the northern control areas drain into the northern cut (BS-5) discharge had to be calculated according equation 1 and is expressed as specific discharge. In addition, the entire area is used as one unit in comparisons, which then accounts for 32% of clear cut and 68% of forest as land cover.

$$BS - 5\ [mm/day] = \frac{(weir\ 5\ [L.s^{-1}] - weir\ 7\ [L.s^{-1}]) * 8640000}{area\ BS - 5\ [dm^2]} \qquad \text{(eq. 1)}$$

where 8640000 is conversion from [L.s^{-1}.dm^{-2}] to [mm.day^{-1}]

Discharge calculations were based on rating curves (eq. 2)

$$q = a * h^{2,5}, \qquad \text{(eq. 2)}$$

where *q* is the discharge (L/s) and *a* is an empirical constant. The value 2,5 as an exponent represents a theoretical value for 90 degree V-notch weir, *h* is the water level above the V-notch.

For each weir rating curves using manual measurements of flow and water level using buckets were established. For the period from September 2004 to December 2007 calculations of specific discharge were based on rating curves used by Sørensen et al. (2009), but specific discharge values were recalculated using the newest available information about catchments areas. From January 2008 updated rating curves according to new manual measurements were used.

Detection of changes

Because precipitation data collected by rain gauges at the sites resulted in different yearly sums, the changes in runoff from year to year at the same sites gave no reliable results. Therefore, runoff-precipitation ratios are used for comparison of annual changes for each site. Further the variance is expressed as relationships of the harvested sites to the reference site (Ref-7). This is given as a ratio of discharge from treated areas and discharge from the reference area (%) in the same time interval. Hence the reference area always represents 100%.

For all sum calculations the calendar year was used instead of the more often applied calculations based on the hydrological year due to possible upcoming rain events in the fall. Those are typically seen in September to November, dependent on meteorological conditions.

Evapotranspiration

Evapotranspiration was determined as a term within the water balance equation (eq. 3) for a closed system (each catchment).

$$\Delta S = P + G_{in} - (Q + ET + G_{out}) \qquad \text{(eq. 3)}$$

where P is precipitation, ET is evapotranspiration, G_{in} and G_{out} are ground water inflow and outflow, ΔS is the change in all forms of storage (liquid and solid) and Q is the stream outflow. For the annual estimates it is assumed that the ground water flows and ΔS are negligible. For the harvested area BS-5 the assumption of a closed system cannot be assumed; the inflow is quantified as the outflow from the weir of the reference area.

Potential evapotranspiration (PET) was estimated according to two formulas with different data requirements. PET was calculated as daily values for days with an air temperature above zero, and summed to the yearly values.

First, the Turc formula, a model with low data requirements (eq. 4), based on radiation and air temperature was applied.

$$PET_0 = 0{,}013 * (23{,}88 * R_s + 50) * T * (T + 15)^{-1} \qquad \text{(eq. 4)}$$

where ET_0 is potential evapotranspiration (mm.day^{-1}), T is daily average temperature and R_s is solar radiation (MJ.m^{-2}.day^{-1}). For the days with humidity lower than 50 % the equation is correct by a_t coefficient, when

$$a_t = 1 + \frac{50 - RH}{70}$$

where RH is daily mean relative humidity.

Secondly the potential evapotranspiration was modelled with higher complexity using the Penman-Monteith equation (eq.5). The Penman-Monteith model is a combined approach using variables describing radiation, temperature, wind speed, humidity and important characteristics of the vegetation cover.

$$\text{PET} = \frac{\Delta * (K + L) + \rho_a * c_a * C_{at} * e_a^* * (1 - W_a)}{\rho_w * \lambda_v * \left[\Delta + \gamma * (1 + \frac{C_{at}}{C_{can}}) \right]} \qquad \text{(eq. 5)}$$

where Δ is slope of vapor pressure curve (kPa.K^{-1}), $K+L$ is the global radiation (MJ.m^{-2}.s^{-1}), ρ_a and ρ_w are air and water density (kg.m^{-3}), c_a is the heat capacity of air (MJ.kg^{-1}.K^{-1}), C_{at} and C_{can} are the atmospheric and canopy conductance (m.s^{-1}), $e_a^* *(1-W)$ is the vapor pressure deficit (kPa), λ_v is latent heat of vaporization (MJ.kg^{-1}) and γ is psychometric constant (kPa.K^{-1}). PET is than the evapotranspiration (m.s^{-1}) and had to be converted into mm.day^{-1} for this application.

Atmospheric and canopy conductance was calculated separately for the 18 m high coniferous forest at the reference area (assuming a leaf area index of 6 and a maximum leaf conductance of 5,3) and for the clear cut assuming 1 m high grass cover with a leaf area index = 3 and a maximum leaf conductance of 6. Values for both, leaf area index and maximum leaf

conductance were then derived from a table given by Dingman (2002). Those values assumed a completely vegetated area.

Based on the assumption that evapotranspiration is the function of precipitation (Dingman, 2002) the Pike formula (eq. 6) was additionally applied for yearly estimates of actual evapotranspiration limited by precipitation.

$$ET = \frac{W}{\left[1+(\frac{W}{PET})^2\right]^{1/2}} \qquad\qquad (eq.\ 6)$$

where *W* is the annual precipitation in mm and *PET* is the calculated potential evapotranspiration.

All evapotranspiration calculations were made for the reference area Ref-7 and for the clear cut site CC-4, which were assumed to be forested till March 2006. The smaller harvested site BS-5 is not included in the ET calculations, as discussed later. Both approaches to calculate PET and ET were then compared with the estimation derived from the water balance equation.

Meteorological data used for calculation evapotranspiration were obtained from the Swedish meteorological service (SMHI). Data sets for several surrounding stations were available and values were interpolated for the 277 Balsjö experimental area using inverse-distance weighting. Different data were available for different stations and years. A summary of the available data is given in Table 1.Temperature and precipitation was measured directly at the experimental sites (temperature: site CC-4 and Ref-7 form June 2008 and precipitation: Ref-7 from January 2007, site CC-4 from May 2009). Field temperature measurements were included in evapotranspiration calculations. Measured precipitation data were used to compare with data derived from interpolation, which was found to results in similar yearly sums.

*Table 1. SMHI stations and data which were interpolated for the 277 Balsjö study area. * Data for the year 2009 were available till 31st of July.*

Station (coordinates)	air temperature	precipitation	wind speed	global radiation	air pressure	humidity
Hemling (63°37´N, 18°33´E)	2004-2009*	2004-2009*	2004-2009*	-	2004-2009*	2004-2009*
Umeå (63°49´N, 20°15´E)	2004-2009*	2004-2009*	2004-2009*	-	-	2004-2009*
Fredrika (64°4´N,12°22´E)	2004-2009*	2004-2009*	2004-2009*	-	-	2004-2009*
Svartberget (64°14´N,19°46´E)	2004-2008	2004-2008	-	2004-2009*	-	-
Balsjö-village (63°55´N,19°11´E)	-	2006-2009*	-	-	-	-

During the snow surveys conducted in March (2005-2009) the amount of snow was measured. A snow core (3 cm diameter tube) was taken every 20 m along six transect running through areas with different cover (open, mire, forest). Transects were crossing the catchments in an east-west direction (Sørensen at al., 2009). From the weight and depth of the snow, the snow water equivalent (SWE) was calculated for two different types of cover, open areas (included mire) and forest. "These values were corrected by the proportion of forest/open for each site and amount of water leaving each catchment in March was estimated" similar to the work done by Sørensen at al. (2009).

Results

Runoff from forests

Runoff in the study area is characterized by low stream flow during winter, which is usually not higher than 1 mm per day during the November – March period; high peak flows during the snow melt in April-May and high flows during summer due to the high precipitation. Summer peaks differ in timing depending on summer storms which are occurring at the different times during the summer months. Autumn months show behaviour depending on temperature, form and amount of precipitation (Fig .1).

The yearly runoff from the forested areas (Ref-7 2004-2009, CC-4 and northern area 2004-2005) is about 58% of precipitation (Tab. 3). In the summer months the ratio is shifting towards lower values due to the higher temperatures and higher evapotranspiration than in the autumn months. During the winter months (November till April) the precipitation falling as snow contributes to approximately 40% of the yearly precipitation. The amount of snow, accumulation and weather conditions determine the spring flood, which generally starts in April and continue till May (Fig. 4).
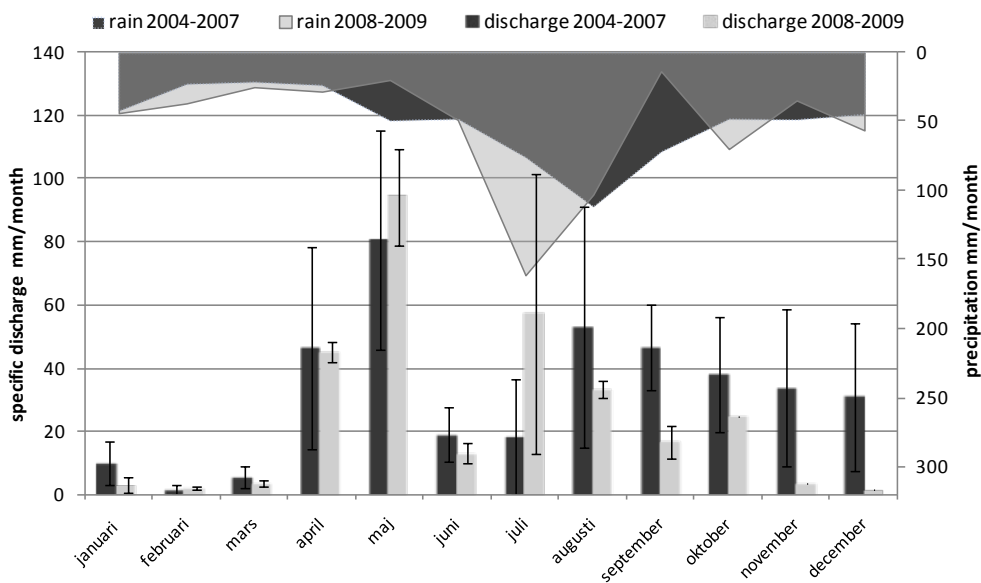

Figure 1: Monthly means of specific discharge (mm) for reference area Ref-7with standard deviations. Precipitation is represented on secondary axis. The time series are divided for period 2004-2007 and 2008-2009 due to the different weir calibration and different rating curves.

Changes after harvesting

Specific discharge

After forest harvesting in March 2006 the runoff from site CC-4, BS-5 and northern catchment increased considerably. The ratio precipitation/specific discharge increased to 72% at site CC-4 and to 71% on whole northern catchment, over the three year period after the treatment (Tab. 3). Furthermore the ratio for site BS-5 increased to 88%. In the pre harvest period (September 2004 – March 2006) the specific discharge (mm/period) from catchment CC-4 was 11% lower than the discharge from Ref-7. Specific discharge at BS-5 was 94% of that at in Ref-7. During the post-harvest period the percentage increased to 119% at CC-4 and 150% at BS-5. The specific discharge for the entire northern catchment, included Ref-7 (68% of area) and BS-5 (32% of area) increased from 98% before clear cutting to 119% after harvest (Tab. 2, 4).

Based on the yearly values the year 2006 increased only slightly but two years after harvest 2007 and 2008 shows much higher increases. The year 2009 implies that the increasing trend in the specific discharge no longer continued and that the annual runoff from the harvested areas starts decreasing (Tab. 2, Fig. 2).

Table 2. Annual specific discharge in mm from all study sites. Sites CC-4, BS-5 and North are expressed compared to the reference site 7 which represents 100%. .* The year 2004 includes September - December, the year 2009 January – October. Values with the gray background represent post harvesting changes.

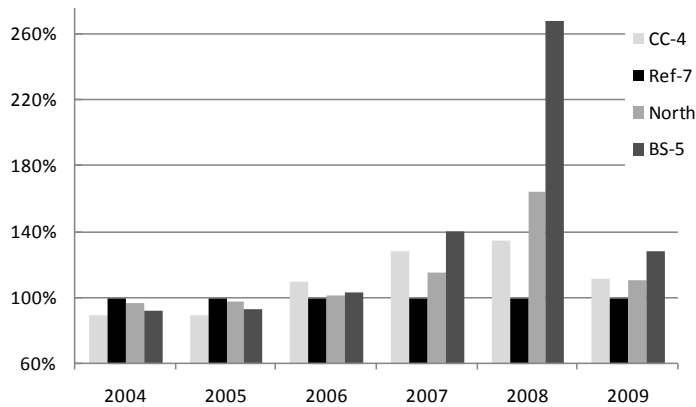| year	runoff mm			
	Ref-7	CC-4	BS-5	North
2004*	**113** (100%)	**102** (90%)	**104** (92%)	**110** (97%)
2005	**356** (100%)	**317** (89%)	**333** (94%)	**347** (98%)
2006	**455** (100%)	**501** (110%)	**472** (104%)	**462** (101%)
2007	**327** (100%)	**421** (128%)	**459** (140%)	**378** (115%)
2008	**269** (100%)	**362** (134%)	**720** (268%)	**442** (164%)
2009*	**400** (100%)	**445** (111%)	**515** (129%)	**443** (111%)

*Figure 2: Yearly specific discharge expressed as a proportion to the Ref-7 when Ref-7 is considered being 100%. * The year 2004 includes September - December, the year 2009 January – October.*

Table 3. Annual specific discharge in mm for all study sites and annual precipitation. Specific discharge is additionally expressed in ratio to precipitation, % in parenthesis. . Year 2004 includes September - December, year 2009 January - July. Values with the gray background represent the post harvesting period.*

year	precipitation mm	runoff mm			
		REF-7	CC-4	BS-net	North
2004*	*186*	113 (61%)	102 (55%)	104 (56%)	110 (59%)
2005	*603*	356 (59%)	318 (53%)	333 (55%)	347 (58%)
2006	*668*	455(68%)	501 (75%)	472 (71%)	462 (69%)
2007	*572*	298 (52%)	421(74%)	404 (71%)	339 (59%)
2008	*590*	269 (46%)	362 (61%)	720 (122%)	442 (75%)
2009*	*411*	321 (78%)	329 (80%)	372 (91%)	340 (83%)

Flow intensities

For 577 days of the pre harvest period, which is included in this thesis, the days with low flows (<1 mm/day) for catchment CC-4 and BS-5 are within 5% difference in relationship to Ref-7, 103% and 95% respectively. The number of days with low flows decreased after harvest for all harvested study sites (Tab. 4, Fig. 3). Before the harvest treatment the days with moderate flows (between 1 and 5 mm/day) were 4% lower for CC-4 and 25% higher for BS-5, than the reference area. The number of days with moderate flows shows the highest shift after the harvest. For 1309 days of the post harvest period the days with moderate flows increased about 67% for CC-4, and 114% for catchment BS-5 compared to the reference site. High flows days (>5 mm/day) appear during the spring floods, summer peaks due to the high precipitation events, and occasionally in autumn (Fig. 4 and 5). After forest harvesting days with high flows also increased, most noticeable for site BS-5, with an increase of 47% in relation to the Ref-7.
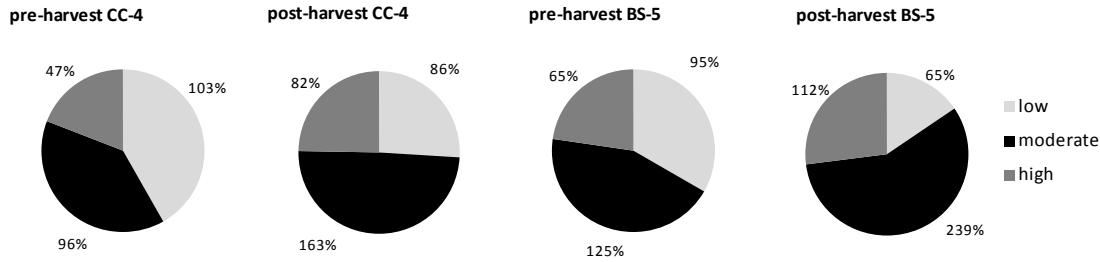
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Figure 3: Percentual expression of days with different flow intensities before and after harvesting on site CC-4 and BS-5. The pre harvest period is from September 2004 to March 2006, the post harvest represents the April 2006 to October 2009 period.

Table 4. Relationship between harvested sites and reference area Ref-7. Pre harvest period is September 2004-March 2006, post harvest April 2006 – October 2009. Runoff shows the ratio between treated areas to reference site in %, mm in parenthesis. Flow intensities are divided into 3 categories and present relationship to the reference site in %, number of days in parenthesis.

runoff				
	Ref-7	CC-4	North	BS-5
pre harvest	100% (478)	89% (428)	98% (467)	94% (448)
post harvest	100% (1420)	119% (1692)	119% (1690)	150% (2127)
flow intensity				
pre harvest				
Low (<1mm)	100% (450)	103% (463)	98% (442)	95% (428)
Moderate (1-5mm)	100% (110)	96% (106)	110% (121)	125% (138)
High (>5mm)	100% (17)	47% (8)	82% (14)	65% (11)
post harvest				
Low (<1mm)	100% (996)	86% (853)	89% (887)	65% (643)
Moderate (1-5mm)	100% (248)	163% (403)	144% (356)	239% (593)
High (>5mm)	100% (65)	82% (53)	102% (66)	112% (73)

Peak flows

Before the forest clear-cut all peak events (spring floods 2005, lower autumn rains September 2004, and summer rains 2005) responded strongest at reference site Ref-7 (Fig. 4, 5) whereas the other catchments show lower peaks. During the spring flood 2005 almost the same amount of water drained from the different catchments. After harvest, discharge peaks were highest at the sites CC-4 or BS-5. For 2007 the highest peaks were found at the site CC-4, for 2008-2009 at the BS-5 (Fig.5), except for one rain event in July 2009 where the highest response was measured at Ref-7.

Spring floods 2006 was slightly delayed (Fig. 6) for all cut areas relatively to the reference probably due to the tree residuals lying on the snow cover and keeping the snow frozen longer (Sørensen et al., 2009). For the following years a similar pattern for the timing of the spring flood is observed even if the water volumes differ (Fig. 6).

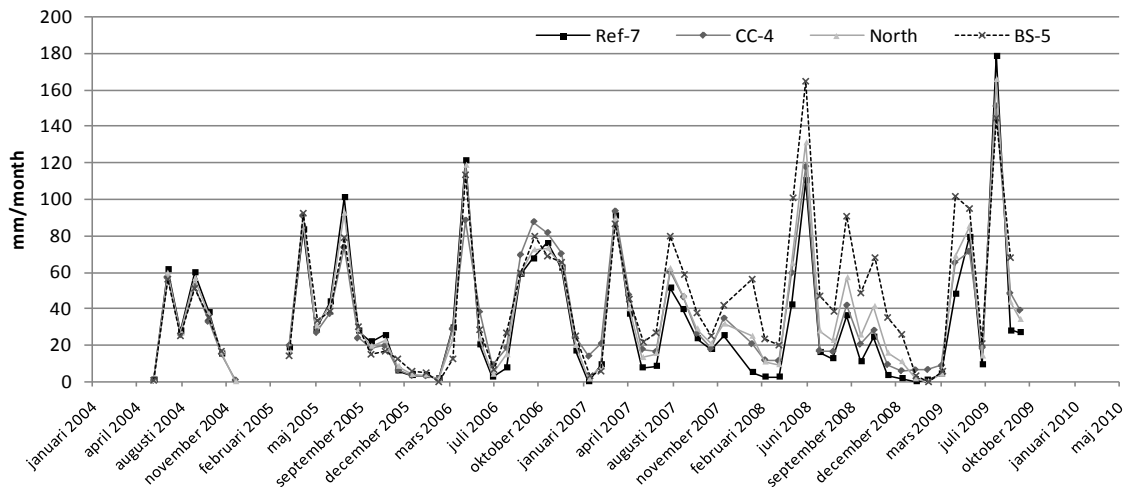*Figure 4: Monthly mean specific discharge from all study sites. The forest harvesting was performed in March 2006.*
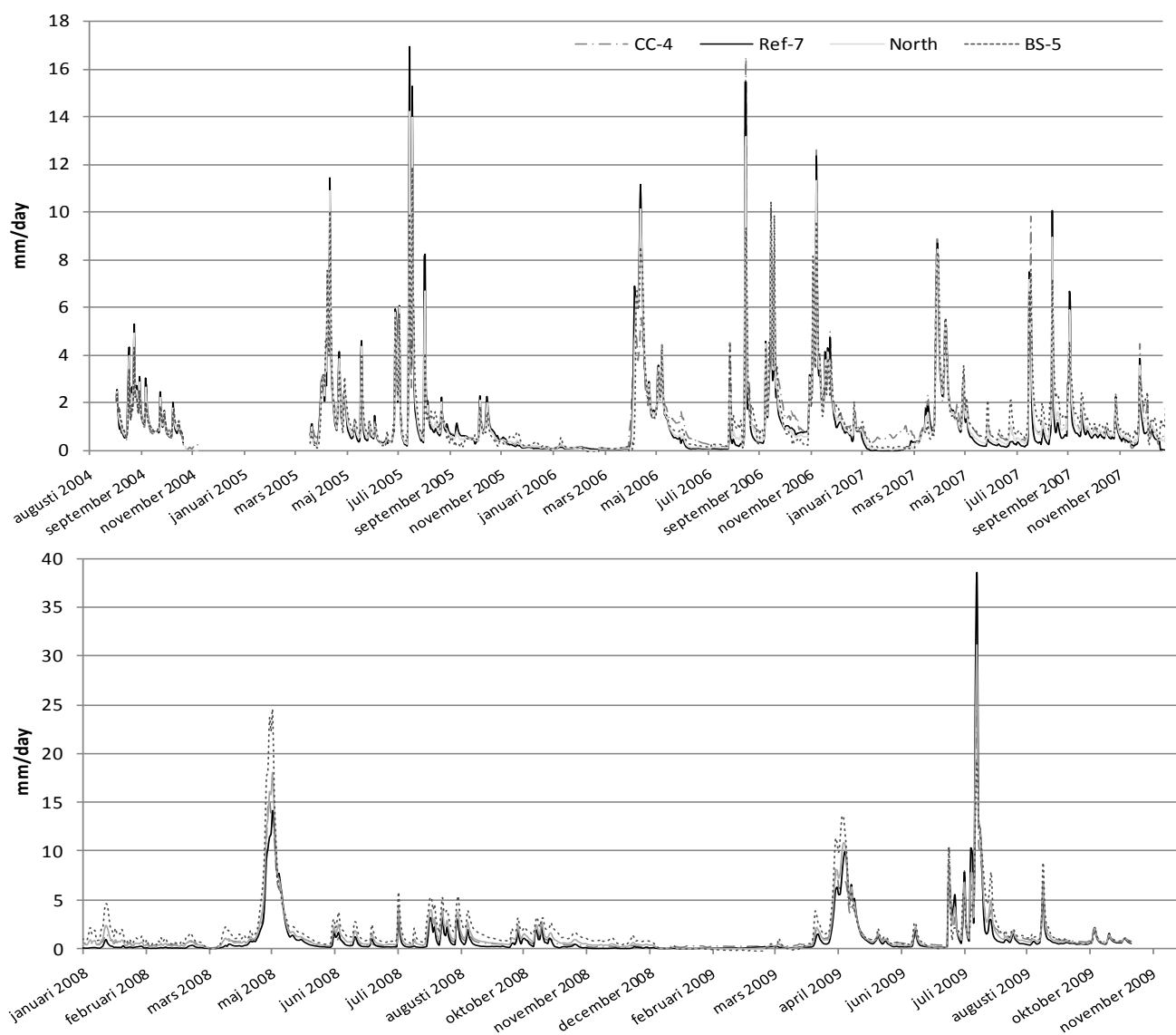
Figure 5: Daily specific discharge for all study sites. The upper figure shows the older measurements till the end of 2007. The lower figure shows values of specific discharge calculated by using updated rating curves from October 2009. The dotted line represents the forest harvesting in March 2006
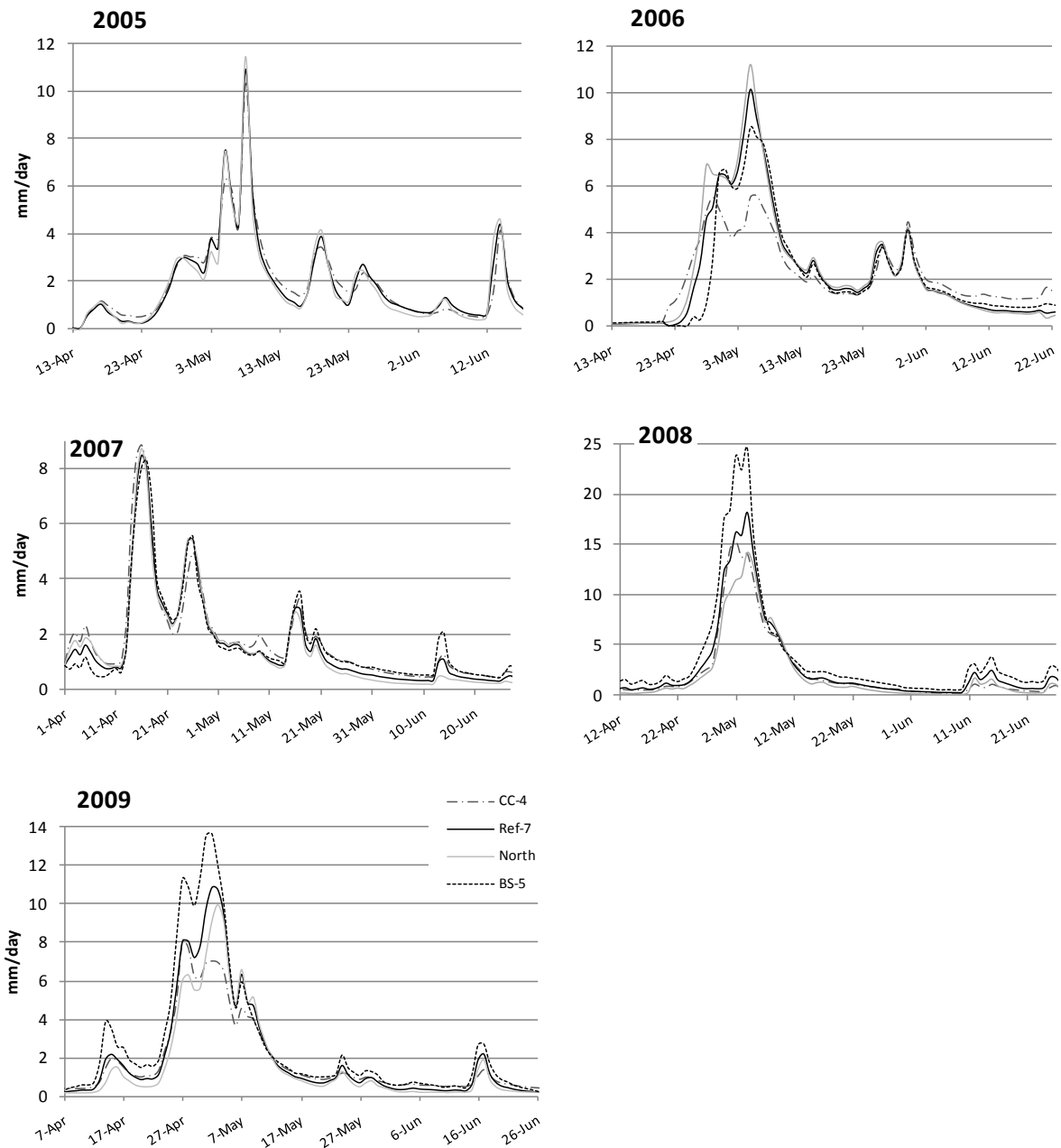
Figure 6: Daily discharge (mm) during the spring floods causes by snow melting from spring 2005 till spring 2009.

Higher spring floods on the harvested sites are caused by the higher snow accumulation on the open areas and therefore higher snow water equivalent during the snow melt. In the forest the snow depth was about 15-25% (between 8 and 18 cm) lower than on the open areas. That is equal to the water equivalent between 33 and 80 mm (depending on the snow conditions and density). The stream runoff at the open sites (CC-4, BS-5) results in a larger amount of water during the snow melt, April - May (Fig.6). The yearly values of snow differences are listed in Table 5 and Figure 7.

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During the winter 2008 the average temperature was about 3 degrees higher than compared to the other years which possibly caused occasional melting of snow which seemingly increased the density of the snowpack. Consequently, the water equivalent increased even though the snow depth was not found to be much higher in comparison to the other years. Therefore, the highest volume of water from all studied years was measured during the spring floods in May 2008.

Table 5. Snow characteristics measured during snow surveys conducted in March 2005-2009. Two types of land cover are distinguished. SWE gives the snow water equivalent. The higher density in 2008 is highlighted as bold numbers.

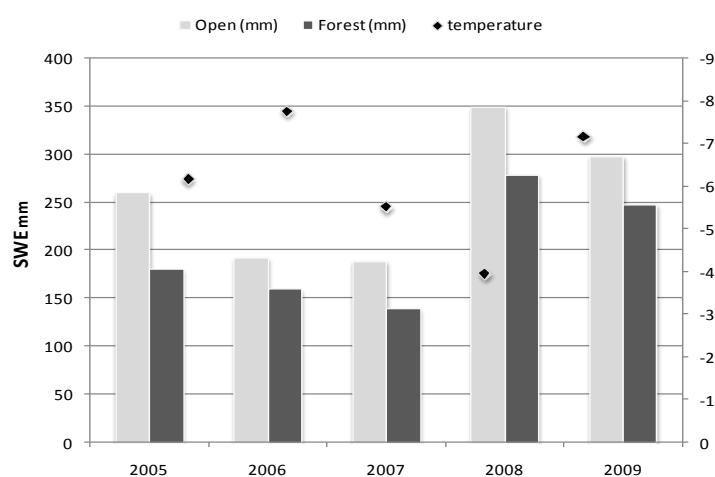| year	cover	Weight (g)	Depth (cm)	SWE (mm)	Density
2005	Forest	127	53	180	0.34
	Open	184	71	260	0.36
2006	Forest	113	45	160	0.36
	Open	136	53	192	0.36
2007	Forest	99	32	140	0.43
	Open	134	42	189	0.45
2008	Forest	197	60	**279**	**0.47**
	Open	247	70	**349**	**0.50**
2009	Forest	176	59	248	0.42
	Open	210	70	298	0.42

Figure 7: Snow water equivalent measured in the end of March. On the secondary Y-axes average winter temperatures in °C (November-March) are presented.

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Evapotranspiration

Water balance residual approach

Assuming no groundwater in and outflow to the catchments, the evapotranspiration can be calculated as the only unknown term in the water balance equation. The other terms in equation, the yearly precipitation and the yearly streamflow must be known.

For the period September-December 2004 the evapotranspiration was 72 mm for Ref-7, 84 mm for CC-4 and 76 mm for the whole northern catchment. For the entire year 2005 the ET at Ref-7 was 247 mm, on CC-4 286 mm and for the northern catchment 256 mm. This indicates for both years before that harvesting the catchment CC-4 had about 16% higher evapotranspiration than reference the site Ref-7. The northern catchment was about 4% higher than the reference area.

Forest harvesting resulted in a decrease in evapotranspiration. Already in 2006 a drop in evapotranspiration can be observed even thought this year was the year with the highest precipitation (668 mm). Whereas for the reference site (Ref-7) a decrease in the precipitation to evapotranspiration ratio from 9% compared to the years before harvesting was observed, the ratio for the harvested site (CC-4) decreased about 21% compared to 2004 and 2005. The coming years show a slow gradual change in evapotranspiration, probably an effect of upcoming new vegetation on the harvested sites. (Fig.8, 9; Tab. 6). Evapotranspiration for year 2009 seems to be very low on all catchments, caused by the limited time interval used for the calculation in the middle of the summer, the period characterized by the highest ET values. Therefore, the results for the year 2009 are possibly not fully representative for the entire year.

For the northern catchment the evapotranspiration results are closer to the values indicated for reference area, Ref-7, than for the harvested site, except the year 2008 which shows comparably low values. The values found for the northern catchment correspond well with the expected values, due to the fact, that 68% of the area is represented by the reference site Ref-7 and 32% are harvested.
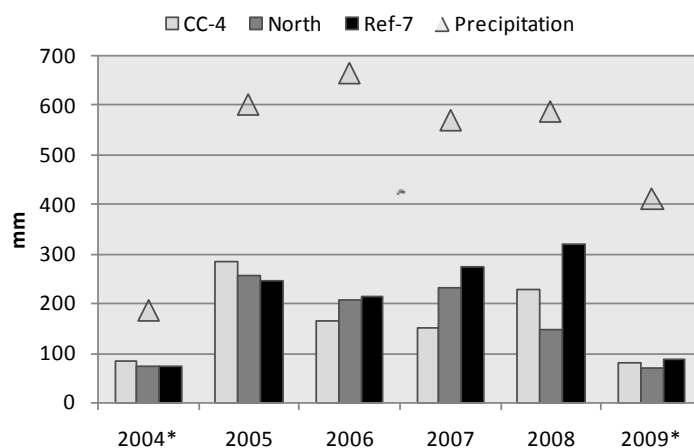

Figure 8: Annual precipitation and evapotranspiration (mm) detected via water balance residual approach. Catchment CC-4 and 32% of the northern catchment were harvested in March 2006.* The year 2004 includes September - December, the year 2009 January – July.

PET

Values of annual potential evapotranspiration calculated with Turc formula (eq. 4) ranged between 320 and 395 mm per year during the years 2004-2008 (Tab.6). Evapotranspiration is not detected in winter months because of low temperatures; months with the highest values are June, July and August. The results for the year 2009 are lower due to the data sets used just until the end of July. For comparability with other results for year 2004 PET was calculated only for September-December period, resulting in a value of 35 mm. The Turc evapotranspiration does not consider any vegetation cover; therefore the results are uniform for all sites without any difference, between forested and harvested sites.

The application of Penman-Monteith approach (eq.5) considers the vegetation covers and hence there are differences between annual PET calculated for the reference area Ref-7 where forest was retained when compared to the clear cut areas. The values for the forested areas ranged between 243 and 341 mm per year 2004-2008, year 2009 is lower, 185 mm for December – July. The PET calculated for a grass cover which was assumed for the harvested areas ranged between 202 and 275 mm yearly for the years 2006-2008, the year 2009 shows again a lower value -158 mm for period December-July. So the evapotranspiration for the grass cover calculated by Penman-Monteith shows approximately 20% lower annual values than for the forested area.

The results calculated with the Penman-Monteith equation for the forested site are approximately about 25% lower than results derived from the Turc formula. For harvested sites the potential evapotranspiration by Penman-Monteith was found to be about 33% lower than the quantification following the Turc approach.
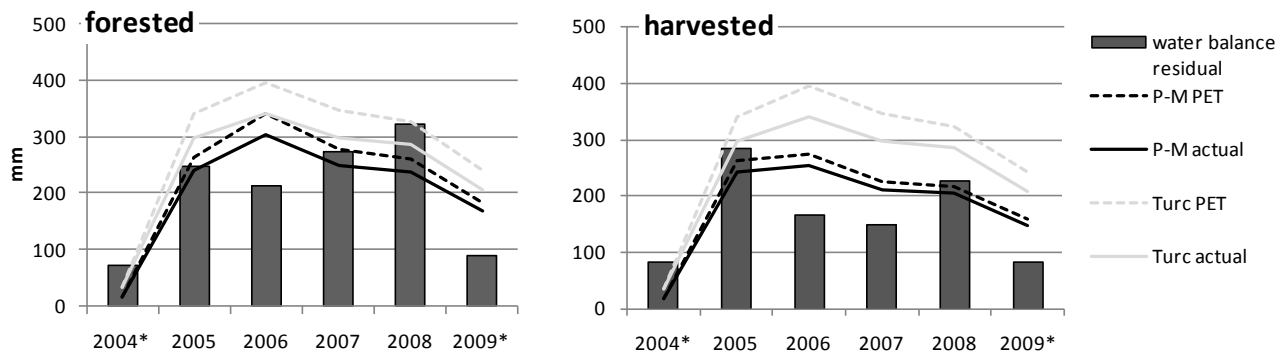

*Figure 9: Comparison of the different approaches for estimating evapotranspiration - water balance residual, Penman-Monteith (P-M) and Turc .Both approaches for calculation potential evapotranspiration are used for Pikes estimation of actual evapotranspiration limited by precipitation(PM actual, Turc actual). * The year 2004 includes September - December, the year 2009 January – July.*

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Relation to precipitation/potential evapotranspiration ratio

Using Pike´s approach (eq. 6) for adjusting potential evapotranspiration (Dingman 2002) by the amount of precipitation all values of PET decrease. The results calculated with Turc model are lowered on average by 13%, most for year 2007 (15%). The year 2007 is characterized by the lowest precipitation from all study years (571 mm). The Penman-Monteith potential evapotranspiration decreased in average about 7% for harvested area and about 9% for forested when the Pike´s formula was used. For both sites the largest difference in PET and Pike´s actual evapotranspiration was observed in 2006, about 8% lower on the harvested site and 11% at the forested site (Fig. 9).

The comparability of calculated PET and ET with the water balance residuals differs during the years and at the sites. The forested site shows similar results to water balance residual in 2005 and 2007 for Penman-Monteith and in 2008 for Turc formula. The water balance residual in 2006 shows much lower values than both values calculated by the Turc and Penman-Monteith formulas. That indicates that the harvesting operations could possibly also influence the reference area.

After the forest harvesting at the site CC-4 the water balance residual was lower for years 2006 and 2007 than the evapotranspiration calculated by both formulas (Fig. 9). In 2008 the values of the water balance residual is 228 mm and the calculated PET by Penman-Monteith is 218 mm, 204 with precipitation adjustment.

Table 6. Summary of calculated evapotranspiration using different methods. For the water balance residual precipitation/evapotranspiration ratios are listed in parenthesis. For both potential evapotranspiration approaches values corrected by Pike´s formula for precipitation adjustment are shown in the parenthesis.*The year 2004 includes September - December, the year 2009 January – July.

		ET (mm) - water balance residual		
	precipitation(mm)	CC-4	Ref-7	North
2004*	*186*	**84** (45%)	**72** (39%)	**75** (41%)
2005	*603*	**286** (47%)	**247** (41%)	**256** (42%)
2006	*668*	**167** (25%)	**213** (32%)	**206** (31%)
2007	*572*	**151** (26%)	**274** (48%)	**232** (41%)
2008	*590*	**228** (39%)	**321** (54%)	**148** (25%)
2009*	*411*	**82** (20%)	**89** (22%)	**71** (17%)
		PET (mm)- Turc approach		
2004*		**35** (34)	**35** (34)	**35** (34)
2005		**340** (296)	**340** (296)	**340** (296)
2006		**395** (340)	**395** (340)	**395** (340)
2007		**347** (297)	**347** (297)	**347** (297)
2008		**324** (284)	**326** (285)	**326** (285)
2009*		**242** (208)	**239** (207)	**239** (207)
		PET (mm)- Penman-Monteith approach		
2004*		**18** (18)	**18** (18)	-
2005		**264** (242)	**264** (242)	-
2006		**275** (254)	**341** (304)	-
2007		**226** (210)	**279** (250)	-
2008		**218** (204)	**260** (238)	-
2009*		**159** (148)	**185** (169)	-

Discussion

The increase in the stream runoff after removal of forest cover found in this study is similar to results of many studies all over the world (Andréassian 2004; Brandt et al., 1988; Martin et al., 2000; Moore & Wondzell 2005; Rosén 1984; Sørensen et al., 2009) and therefore the finding can be generalised, even though the behaviour of the stream after forest harvesting is result of the forest characteristics and ecological features as well as regional climate and local meteorological conditions (Martin et al., 2000). Therefore, a prediction of stream response on forest removal becomes difficult, especially more when one considers the unique meteorological conditions in Northern Sweden.

After the treatment at the Balsjö study sites, the increase in discharge at the clear cut site CC-4 is within a 30% interval and the ratio of runoff/precipitation increased from 52% to 72%. This corresponds with other results observed in Sweden (Rosén, 1984; Sørensen et al., 2009). Furthermore, Andréassian (2004) as well as Sørensen et al. (2009) describe several studies showing noticeable increases of low flow intensities after forest removal conversely to a decrease of low flows after reforestation. This corresponds with results in this study showing a decrease of days with low flows and a marginal increase of days with moderate flows. In fact, the low flow intensity increased to the level of moderate flows, resulting in a decrease of days with low flows. The ratio of days with intensities low: moderate: high changed from 103:96:47 (in percentage) before harvest to 86:163:82 after harvest in relation to the reference site.

The second harvested site BS-5 embodies a similar runoff and flow response during the post harvest period April 2006 - December 2007. Annual discharge for year the 2008 is about 317 mm higher than the discharge for year 2007 when the precipitation increased by about 20 mm. That gives a yearly discharge about 130 mm higher than precipitation during the same period which is practically impossible for assuming a closed catchment system. Therefore, the site BS-5 has to be assumed as an open system with possible groundwater inflows. Furthermore the calculations for BS-5 beginning in December 2008 are possibly affected by one or more of the changes which will be discussed in the following section.

1) Changes in flow calculations, different rating curves and calibration,
2) Inaccurate precipitation information,
3) Inaccurate catchment area information,
4) Soil preparation in May 2008.

Discussion of possible factors affecting the discharge calculations for the BS-5 catchment

1) First, the calculations starting January 1, 2008 were based on updated rating curves for all weirs. The rating curve for catchment CC-4 changed just slightly in comparison to the rating curves for weir 7 and 5, which could explain the changes for catchment BS-5.
   Until the end of 2007 all calculations of specific discharge were based on flow rates (l/s) and rating curves used by Sørensen et al. (2009). He reports the study period September 1, 2004 – April 1, 2008 at the 277 Balsjö experimental sites, with the older catchments area measurements.

For the unification of the results in this study the updated areas of the catchments were used for the entire study period (2004 - 2009). Hence the differences between results shown in this thesis and results published by Sørensen et al. (2009) can be found. Calculation using the updated rating curves can be one of the explanations why the higher discharge started to appear exactly from the beginning of 2008.

Moreover, the calculations of flows (l/s) for site BS-5 (eq.1) do not necessarily model the exact process, due to the possible different timing of the high flow events. The subtraction than can provide an inaccurate result. Despite this, this process has been successfully used before (Sørensen et al., 2009).

2) In this study I was assumed that the precipitation data are reliable for two reasons. Precipitation was interpolated from surrounding stations which is a common method for completing incomplete data sets (Dingman 2002). Furthermore, one of the stations included in the calculations is placed less than 13 kilometres from the study area, in Balsjö village. Therefore, it was believed that the interpolated precipitation could be inaccurate in daily values but not in the annual total. Furthermore this interpolated annual precipitation is adequate with precipitation measured directly on study sites (Ref-7) and also corresponded well with the timing of stream responses.

3) The catchment areas were defined using Digital Elevation Models using field observation to overcome uncertainties. The newest estimations in the field (October, 2009) deduced site sizes of about 45 ha for CC-4, 14 ha for BS-5 and 23 ha for Ref-7. The catchments areas used by Löfgren et al. (2009) and Sørensen et al. (2009) were 37 ha for CC-4, 11 for BS-5 and 25 for Ref-7. Furthermore the area measurement conducted in June 2009 deduced about 16 ha for BS-5 and 25 ha for Ref-7 witch indeed shows the uncertainties in these area estimations. To decide about what is right (i.e. areas with a very low relief and/or, ditches) is difficult and hence the catchment areas could be assumed to be one of the possible reasons for the observed error in specific discharge.

4) One of the explanations for increased discharge in 2008 and, partly in 2009, may be the performed soil preparation at the harvested areas in May 2008. It has been shown before that the soil preparation may alter the soil characteristic such as an increase of soil temperature, porosity water content and water retention (Heiskanen et al., 2007; Mäkitalo 2009). This could result in changes of the water regime at the treated sites which can cause changes in runoff (Heiskanen et al., 2007). Furthermore the mix and loss of topsoil during soil scarification disrupts the grass cover on the clear cut areas which could result in a decreased transpiration. The amount of rain not used for transpiration could contribute to the stream and cause the higher runoff. Nevertheless, the soil preparation was performed at both harvested sites (CC-4, BS-5) but no remarkable response on CC-4 catchment was observed.

To summarize, the uncertainties at catchment BS-5, the assumption of a non-closed system for the water balance, together with the uncertainty of the factors discussed above (catchment areas, updated rating curves and soil preparation) can lead to questionable results. Therefore, special attention should be paid to catchment BS-5. From the beginning of 2008, the results for the entire northern catchment are assumed to be possibly biased similar to the results for site BS-5.

The role of snow after harvesting found in this study is very important for the spring floods caused by snow melting. Due to the removal of forest canopy, the greater accumulation of snow on the open areas was observed also in other studies (Rosén 1984; Sørensen et al., 2009; Troendle & Stednick 1999). Further Jost et al. (2007) report that the variability of snow accumulation at the watershed-scale is also influenced by topography, with elevation and aspect as the dominant controls. Therefore, the investigation of changes of hydrological variables after forest harvesting should take vegetation changes as well topographical characteristics into account. The higher snow accumulation cause a higher SWE which is crucial for the spring floods during snow melt. Therefore, it is supposed that the snow melting on the open areas will cause higher stream flow due to the greater snow accumulation compared to the forest (Jost et al., 2007).

The spring flood before forest harvesting showed a similar amount of water leaving both catchments in the entire northern site (BS-5 and Ref-7) which is in contrast to the spring flood after forest cutting when the highest floods were observed for the harvested site BS-5 (See Fig. 6). The spring floods at CC-4 shows lower amounts of water during the snow melt compared to the forested reference area. The snow accumulation measured at catchment CC-4 shows similar snow depths and SWE as the measurements at BS-5. Therefore, the lower amount of water ends in the stream draining CC-4 during the snow melt is possibly caused by the topographical factors as is discussed in Jost et al. (2007).

The expected decrease in evapotranspiration after the forest harvesting is also shown by other studies (Bosh & Hewlett 1982; Jutras et al., 2006; Moore & Wondzell 2006; Rosén, 1984). This behaviour can be explained by a number of processes as the removal of the forest canopy strongly reduces interception and transpiration, which are often found to equally contribute to summer evapotranspiration (Jutras et al., 2006). Further Moore & Wondzell (2005) report that the major role of interception is biggest when the amount of precipitation is small as i.e. during small storms, where almost all rain can be intercepted and lost from the dense forest cover. They confirm that between 10 and 30 percent of rain can be intercepted from a coniferous canopy. Furthermore, the same authors have noted that fog and cloud drip can be intercepted by trees, resulting in it being collected on the forest ground. Tree transpiration is assumed to be higher than grass; therefore total forest evapotranspiration is expected to be generally larger than that of other vegetation types (Matsumoto et al., 2008).

The actual annual evapotranspiration quantified in study by the water balance approach decreased from 286 mm for 2005 to 167 mm in 2006 at the harvested site. The decrease of evapotranspiration/runoff ratio was from 47% in 2005 to 25% in 2006. Troendle & Stednick (1999) report, that typically timber harvest reduces ET by 50-55%. Bosh & Hewlett (1982) compare 94 catchment studies from different climatic zones and report the changes in water yield and evapotranspiration. They declare that the variation in results is extreme and additionally complicated by the variation in conditions in the studied area. The changes observed in the 277 Balsjö experiment do not reach as high values as reported by Troendle & Stednick (1999) for some sites, but they are within the given range reported.

Between 2005 and 2006 a slight decrease of evapotranspiration was observed at the reference site (see Tab. 6) even though the annual precipitation was higher in 2006 (about 60 mm). Therefore, the decrease of evapotranspiration either at the harvested site or the reference forested catchment is assumed to be partially caused by other meteorological factors (snow, temperature, radiation, rain storm intensities) or due to the forest harvesting operations.

The evapotranspiration changes became more interesting in 2007. The ET detected by the water balance approach at the reference site increased about 60 mm. At the harvested catchment the ET decreased about 16 mm. The ET/runoff ratio increased at the reference site from 32% in 2006 to 48% in 2007, from 25% to 26% at harvested site which results in total of 123 mm difference in evapotranspiration between the forested and harvested site.

Two years after the harvest, in 2008, the annual evapotranspiration at the harvested site increased again back to values of 228 mm (37% for the ET/runoff ratio). The explanation of this behaviour could be the newly established vegetation cover. Nevertheless, the soil preparation (causing the disruption of vegetation cover) in May 2008 was performed therefore the noticed increase of evapotranspiration is probably caused by the changes in evaporation after the ground preparation.

Typically the evapotranspiration is assumed to be limited by many factors such as available energy, water storage in soil, the heat storage effect of vegetation cover. Different PET models include different variables but even most data intensive models (such as the Penman-Monteith model) give only an estimate of potential ET. Therefore the calculated PET is always overestimated and provides higher values than the actual ET should be (Dingman 2002; Cienciala et al., 1999; Papadoupoulou et al., 2003). Oudin et al., (2004) compared different PET models and evaluate their ability to estimate evapotranspiration. They indicate that the combined Penman-Monteith method is typically considered as the most physically representative by many hydrologists.

In our study we conclude that the Penman-Monteith approach calculated for different vegetation covers gives a good estimate of annual evapotranspiration at the 277 Balsjö studied sites (Fig. 7). The values calculated for the years 2005, 2007, and 2008 partly, at the forested site correspond fairly well with the water balance residual, in 2005 and 2008 at the harvested sites respectively. In contrast, the annual PET in 2006 and 2007 seems to be noticeably higher than the water balance residual at the harvested site. One fairly simple explanation for this behaviour could be that in the application of the Penman-Monteith formula in this study it was assumed that a full vegetation cover as grasslands represents the harvested sites. This condition might just be partly fulfilled directly after harvesting operations when the ground vegetation is disturbed.

After the application of Pike´s formula the values of Penman-Monteith PET decreased about 8% in average. It can be assumed that this combined approach gives a better estimation of the actual evapotranspiration – the values were found to be closer to those estimated by the water balance residual approach, especially at the forested sites, where the role of transpiration is higher.

When the Turc method was used the values of PET were generally higher than Penman-Monteith approach. Further the Turc formula gives approximately 35% higher values than the water balance residual at the harvested site and about 20% higher at the forested (the year 2008 was excluded for this evaluation, due to the reasons discussed earlier). Therefore, it can be assumed that the Turc formula is more suitable for the forest cover than for the grassland in the conditions of the boreal region.

Approximately 50 methods to estimate PET were developed during the last decades. Due to their different assumptions and different input data requirements the provided results are usually inconsistent, especially more when these are suggested for specific climatic regions

(Lu et al., 2005). For instance Oudin et al. (2004) as well as Fontenot (1999) found the same efficiency of the relatively simpler Turc approach as the combined Penman-Monteith formula for the estimation of PET for a reference surface such grassland. The results presented in this thesis illustrate the more accurate PET reached by the Penman-Monteith approach than Turc, especially at the harvested site. The relationship between potential and actual evapotranspiration differs among the different models and the question which model of PET gives the most usable results must indeed be considered carefully. Hence Lu et al. (2005) recommend that the usability of a certain method to estimate PET should be validated in the field before it is used.

Conclusion

Logging disturbance in a boreal forest catchment can clearly alter the behaviour of streams and have consequences for the watershed. After the forest removal, annual specific discharge was found to increase strongly, evapotranspiration decreased and the snow accumulation was higher on the open areas. However, most studies from the boreal forest show similar effects of forest harvesting (Buttle and Metcalfe 2000; Rosén 1984; Sørensen et al., 2009) even though the precise extent of the caused changes is difficult to predict. The characteristics of the watersheds together with the local meteorological conditions make every study unique. The removal of the forest and its influence on the water balance of watersheds highlights the fact that the aquatic and terrestrial ecosystems are closely linked (Buttle et al., 2005).

The Balsjö experiment presents results from the 31 months after forest cutting. It has been documented that short time studies focusing on the shorter time scale can provide results showing extremely high differences between years before harvesting and subsequent periods. Further, the increase of peak flows and runoff was observed only during the first several years after harvest (Martin et al., 2000). Therefore, it seems as if only the longer time studies can fully quantify the effect of forest disturbance and the consequences of a treatment in its full extent. Thus it would be at most interesting and advisable to place the 277 Balsjö study in a longer perspective and pursue the hydrological measurements for a longer period.

Acknowledgements

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             A comparison of protein complexation capacity among six boreal species and the
             consequences for nitrogen mineralization

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             Markberedningsresultat och plantbildning med såddaggregaten Humax 2-4 och KSM-
             såddskopa

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