Influence of Topography and Forestry on Catchments: Soil Properties, Runoff Regime, and Mercury Outputs

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Cover photo: Subsurface sun reflections caught by Marcus Wallin in the V-notch weir at site BS a.k.a. Dam 5 a.k.a. North a.k.a. WS9.

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Abstract

The dynamic development of terrestrial and aquatic environments in boreal catchments is controlled by the factors of parent material, climate, topography, biota, time, and anthropogenic activity. This thesis explores two of these factors, topography and the anthropogenic activity of forestry, as well as their control on the redistribution of solutes in the landscape.

On a local scale for two undisturbed sites, the calculation of the topographical wetness index, TWI, was varied to better correlate to site properties. TWI values derived from large scale topographical features correlated better with soil pH and distribution of vascular plants (r^2=0.5-0.8), whereas a more locally derived TWI correlated better with soil moisture conditions (r^2=0.7-0.8). Even on a regional scale, the TWI correlated well with soil properties confirming its major control on soil evolution for the relatively young soils of the Swedish boreal zone.

The disturbance of forest harvest in March 2006 according to best management practice was found to increase the annual flow by 35%, with a larger effect during the growing season (50-70%) than the dormant season (10-30%). Compared to other studies the change in concentration and export of mercury (Hg), methylmercury (MeHg), and total organic carbon (TOC) was minimal. During summer 2007 high frequency episode sampling, though, there was a significant increase in dissolved organic carbon (DOC) for the harvested sites compared to the reference sites.

The results confirm that topography is a potential indicator for various site properties, such as soil chemistry, in the upland zone as well as the near stream zone. It is also a relatively neglected source of information that can be refined further. Forestry's impact on the mercury load to the aquatic environment was found smaller in this study compared to other similar studies. This might be due to the thick snowpack that protected from soil impacts during harvest, as well as the fact that site preparation had not been conducted, and that the near stream zone was left intact.

Keywords: boreal, topographic index, TWI, soil, forestry, mercury, methylmercury, runoff, TOC, DOC, episodes.

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Dedication

Til Bedste

The population problem has no technical solution; it requires a fundamental extension in morality.
– Garrett Hardin

Panta rei

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Sørensen, R., Zinko, U. & Seibert, J. (2006). On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences,* 10, 1-12.

II Seibert, J., Stendahl, J. & Sørensen, R. (2007). Topographical Influences on Soil Properties in Boreal Forests. *Geoderma,* 141(1-2), 139-148.

III Sørensen, R., Ring, E., Meili, M., Högbom, L., Seibert, J., Grabs, T., Laudon, H. & Bishop, K. (2009). Forest Harvest Increases Runoff Most during Low Flow in Two Boreal Streams. *Ambio,* 38(7), 357-363.

IV Laudon, H., Hedtjärn, J., Schelker, J. Bishop, K., Sørensen, R. & Ågren, A. Response of Dissolved Organic Carbon following Forest Harvesting in the Boreal Forest. *Ambio,* 38(7), 381-386.

V Sørensen, R., Meili, M., Lambertsson, L., von Brömssen, C. & Bishop, K. The Effect of Forest Harvest Operations on Mercury and Methylmercury in Two Boreal Streams: Relatively Small Changes in the First Two Years prior to Site Preparation. *Ambio,* 38(7), 364-372.

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The contribution of Rasmus Sørensen to the papers included in this thesis was as follows:

I Data for this paper was collected before the respondent began his studies. Data handling, modelling and writing was mainly done by the respondent.

II The respondent was part of the data interpretation and writing process of the paper.

III The respondent participated in designing and planning of the study, as well as in the field work. Data handling and calculation, writing and publishing was mainly done by the respondent.

IV Runoff data for this publication was mainly provided by the respondent. The respondent took part in the writing process of the paper.

V The respondent participated in designing and planning of the study, as well as in the field work. Data handling and calculation, writing and publishing was done by the respondent to a large degree.

Abbreviations

DEM	Digital Elevation Model
DOC	Dissolved Organic Carbon
Hg	Mercury
Hgtot	Total Mercury
MeHg	Methylmercury
POC	Particulate Organic Carbon
SEPA	Swedish Environmental Protection Agency
SFA	Swedish Forestry Agency
SRB	Sulphur Reducing Bacteria
TOC	Total Organic Carbon
TWI	Topographical Wetness Index

1 Introduction

Water is an important solvent moving through the landscape, and is thus an important redistributing agent in boreal catchments. The relatively young soils of the boreal zone are dynamic and continuously undergo development. The evolution of a natural soil is traditionally described as a function of the five soil forming factors: parent material, climate, topography, biota, and time (Jenny, 1941). Four of these controlling factors are interconnected by hydrology: the influence of climate is to a large extent the influence of precipitation, topography has a strong influence on the hydrological flow paths of precipitated water, the distribution of biota is influenced by the varying access to water, and time is among others an expression of the duration of exposure to water. The redistribution of solutes takes place not only within the soil column or at the hillslope scale, but also from the hillslope into streams draining the soils of water. Subsequently, hydrology is also of great importance for the formation and evolution of soils.

In addition to the five natural soil forming factors, there is a sixth component that can alter the properties of a soil as well as the chemical composition of stream water. The sixth soil forming factor is the anthropogenic influence, such as the cultivation of land. Forestry is one such activity that alters the natural dynamics within a catchment. Another anthropogenic activity is the emission of harmful substances, such as mercury (Hg). Long range transports of mercury emissions, mainly from combustion of fossil fuels, have caused increased Hg deposition even in remote areas, such as the Swedish boreal zone. One result of that may be decreased soil respiration rate and thus decreased rates for organic decay (Bringmark and Bringmark, 2001). Elevated Hg emission has also contributed to Hg-levels in freshwater fish above recommendations for human consumption in tens of thousands Swedish lakes (Johansson, et al., 2001). The Hg itself is not available for bioaccumulation in the food chain before methylation, which takes place under certain conditions, e.g. in sediments, riparian zones and wetlands (Schuster, et al., 2008). Due to increased MeHg in waters and the biota after forest harvest operations, the role of forestry in mercury production and mobilization has been under debate. Forestry was recently estimated to contribute between 9-23% of the mercury in the fish of Swedish forest lakes (Bishop, et al., 2009). The hydrological effects of forest harvest may be a major component of this forestry effect on Hg. Forestry can also affect dissolved organic carbon (DOC). Since DOC is a major control on Hg mobilization and methylation, its response to forest harvest is thus of great interest for Hg dynamics at the catchment level.

This thesis explored both the influence of topography on the properties of boreal soils, and the influence of forestry on the runoff regime as well as the DOC and mercury outputs to a boreal stream.

2 Background

2.1 Topography and redistribution of solutes in the landscape (papers I & II)

The role of topography in a landscape has long been widely acknowledged for its role in soil formation. Beven and Kirkby (1979) attempted to summarize the hydrological conditions for any given point in a landscape by applying an index value derived from the upstream drainage area as well as the drainage conditions at the point. Thus the topographic wetness index (TWI) combines the specific upstream area, a, (a=A/l, where A is the upstream area and l is the contour length), with the slope, β, in the expression ($\ln a/\tan\beta$). TWI has been found to correlate well with various soil properties, of both physical (Moore, et al., 1991) and chemical character (e.g. Giesler, et al., 1998). Consequently, even the distribution of vascular plants in the landscape correlates to TWI in some studies (Zinko, et al., 2005).

The control of topography on soil properties varies among areas as well as among the properties of interest. The effect of topography is more pronounced on young and rolling landscapes than old and level landscapes (Birkeland, 1999). The soils of the Swedish boreal zone are relatively young and the landscapes are hilly, which is why the effect of topography can be expected to be significant for soil properties.

The TWI is usually calculated from gridded elevation data in a digital elevation model (DEM), and can be derived in various ways depending on assumptions about the movement of water at the hillslope scale. Different algorithms are used for these calculations (Güntner, et al., 2004; Quinn, et al., 1995; Tarboton, 1997; Wolock and McCabe, 1995).

Paper I describes an optimization of the TWI-calculation regarding the factors mentioned above to better correlate to different soil- and biota properties at the point of interest.

Paper II applies the TWI to data on soil properties for 4,000 sample plots from almost all of Sweden to study the behavior of correlation between TWI and soil properties on a large regional scale.

The studies described in papers I and II take place in systems not recently subjected to the sixth soil forming factor of forest harvest.

2.2 Forestry and Hydrology (paper III)

Vegetation is not only influenced by the topographically induced variation in hydrology, it also plays a key role in the water balance. Logging a forest reduces transpirational water demand and interception temporarily and opens up for larger snow accumulation, causing the ground water levels to rise as well as runoff to increase. This alteration of the hydrological dynamics itself, as well as the solutes transported by the water, can have a large impact on the aquatic environment.

Runoff regime changes induced by logging have been recognized for a long time, but differ among regions and sites (Andréassian, 2004). Studies under Swedish conditions have been scarce, and the northern half of the country is not represented among them. The latest Swedish study was conducted a quarter of a century ago. In these Swedish studies the runoff change was separated into dormant season and growing season, and different patterns emerged for different areas (Lindroth and Grip, 1987). Thus, site specific information is of interest to better understand the behavior of the hydrological processes at the site and to expand our knowledge in more general terms.

Paper III investigates the changes in flow regime for different seasons and flow rates after forest harvest in the Balsjö catchment area in the boreal zone of northern Sweden.

2.3 DOC – the vehicle transporting multiple substances in catchments (paper IV)

One of the most important solutes in forest systems is organic carbon. Total organic carbon (TOC) binds strongly to many other ions and acts as a vehicle for various substances on their travel through the catchment area, such as organic substances (Niederer, et al., 2007), aluminium (Cory, et al., 2006), and mercury (Ravichandran, 2004). Water quality is thus controlled by TOC to a very large extent in these systems (Laudon, et al., 2005). Particulate organic carbon (POC) is the solid component, operationally defined as not passing a 0.45μm filter, that together with dissolved organic carbon (DOC) comprise TOC. While POC is a key factor in the mobilization of various substances in some areas (Schuster, et al., 2008), it plays a minor role in the boreal forest of northern Sweden (Gadmar, et al., 2002). Here there has been found no statistical difference between TOC and DOC analyzed from the same sample in a large number of stream water samples form a catchment area close to the Balsjö study area (Laudon and Buffam, 2007).

The continual degradation of organic material leads to a generally higher level of DOC in superficial soil horizons in the boreal forest, particularly downslope near the stream (Giesler, et al., 1998). Forest harvest induced flow increases and elevated ground water levels result in shallower soil horizons being more frequently exposed to lateral ground water flow (Kreutzweiser, et al., 2008), which will increase the DOC-leakage in more superficial soil layers. This phenomenon is well known from episodes of high flow in the boreal forest (e.g. Hinton, et al., 1998).

Paper IV describes a study where the post harvest changes in DOC concentration and transport during growing season are investigated in the light of hydrological effects of forestry, to see if there are increases in DOC after harvest.

2.4 Hg-threat – MeHg-production and mobilization (paper V)

The fish in about half of the Swedish lakes have mercury levels exceeding recommendations for human consumption (Johansson, et al., 2001). This severe situation is partly a result of long range transports of human induced Hg emissions. The boreal forest landscape has a large storage of Hg strongly bound to soil organic substances. Even though the storage is large enough to cause Hg leakage for many years to come (Meili, et al., 2003), the management of the forest is critical for the release rate of Hg from the soil to receiving streams and lakes, and eventually to aquatic organisms and quite likely the form (methylated, particulate or dissolved)(Shanley, et al., 2005).

Methylmercury (MeHg) is the Hg-species that is taken up by organisms and bioaccumulates in the food web. The methylation of Hg is caused primarily by sulfur reducing bacteria (SRB) under certain redox conditions (Gilmour, et al., 1992). The presence of sulfur, Hg, and an electron donor, e.g. DOC, and temperature conditions influence the net methylation rate (Mitchell, et al., 2008).

One effect of forest harvest is an increase in ground water levels and soil moisture that influences redox conditions in ways that stimulate SRB and promote methylation. Shallower ground water levels also enhance the connectivity from the terrestrial to the aquatic environment, increasing the mobilization of solutes. Furthermore soil temperature can rise in a clearcut area relative to a forested area, which may also influence net methylation.

3 Objectives

The general aim of this thesis was to contribute to the understanding of how hydrological processes influence boreal soil as well as the runoff outputs of DOC and mercury, particularly in a managed forest landscape. The specific objectives were:

- To optimize the interpretation of topography to better capture the variability of soil- and site properties in the landscape (Paper I).
- To investigate the generality of topographic influence on soil properties on a regional scale (Paper II).
- To analyze the effect of logging on the runoff regime (Paper III) as well as DOC (Paper IV) and Hg outputs (Paper V) at the catchment scale.

4 Methods and Results

4.1 Paper I

The hydrological flow through the landscapes can be assumed to take different paths. The TWI can be calculated in different ways to reflect these different assumptions. The calculation methods differ in the way the accumulated upslope area is routed downwards, how creeks are represented, and which measure of slope is used.

For two 25 km^2 podzol dominated areas, Åmsele and Kälarne, in the boreal zone of northern Sweden the TWI was correlated to site characteristics: pH, vascular plant species richness, ground water level and moisture. To optimize the correlation between TWI and site characteristics the calculation of the TWI was adjusted as follows:

Routing of flow: The routing of flow from one grid cell in the DEM to the next cell or cells (up to eight directions) can either have ordinal or cardinal directions as proposed by Quinn (1995), or it can be routed in any direction as proposed by Tarboton (1997).

Exponent: In the case of more than one receiving cell in the DEM, the proportions of flow divided into either direction is divided by the expression: $F_i = \tan\beta^h_i / \sum \tan\beta^h_i$. A high value of h makes the steepest direction receive more accumulated area than a low value of h.

Creek initiation threshold area: A DEM cell containing a creek needs to be considered explicitly. A creek initiation threshold area (cta), is the amount of accumulated area at which a creek is expected to appear. The accumulated area of a "creek cell" in the DEM is usually routed downslope as "creek area" and not considered in the calculation of *a* in downslope cells. However, one question is if the area below cta should be routed downwards and contribute to the specific accumulated upstream area, *a* (i.e., only the area exceeding cta is treated as creek area) or if all accumulated area should be routed downwards as creek area. We tested both variants and called them cta-down and cta-ordinary.

Cta: for cta-ordinary, different areas can be chosen to represent the creek initiation threshold area.

$\tan\alpha_d/\tan\beta$: The slope of a certain point (represented by the midpoint of the DEM cell) can be represented either as the local slope $\tan\beta$, or it can be represented by the drainage conditions further away, $\tan\alpha_d$ (distance *d*), from the point than one DEM cell. Different values can be given for *d* depending on assumptions for the influence of drainage conditions on the TWI.

d-beeline/d-along flowpath: The distance of *d* can be represented either as the beeline distance to the closest cell *d* meters away or it can be assumed to follow the flow path.

A combination of all these different methods of calculating TWI gave rise to 2688 different values for TWI for each DEM cell.

It turned out that one optimal calculation method did not emerge. Instead, two groups of variables correlated better with different TWI calculation methods (table 1).

Species richness of vascular plants and pH can be seen as an integrated measure of long term conditions on a site, and were best correlated to similar TWI calculation methods dominated by larger scale variations. Variations in hydrological conditions, on the other hand, were associated with variations on a much shorter spatial and temporal scale.

Table 1. Best Spearman rank correlation coefficients obtained for the single measured variables at each site and for different groups of variables. Correlation coefficients for correlations where the particular variable is included in the respective group are in bold.

	Best possible correlation for each variable	Best correlation for groups of variables				
		Species richness and pH	Groundwater, soil moisture and wetness degree	LP site (Åmsele)	HP site (Kälarne)	All
LP site (Åmsele)						
Species richness	**0.604**	**0.587**	0.556	**0.597**	0.570	**0.580**
pH	**0.519**	**0.505**	0.492	**0.513**	0.497	**0.498**
Groundwater	**0.772**	0.582	**0.772**	**0.743**	0.711	**0.722**
HP site (Kälarne)						
Species richness	**0.795**	**0.765**	0.667	0.716	**0.730**	**0.739**
pH	**0.845**	**0.840**	0.757	0.795	**0.798**	**0.802**
Groundwater	**0.898**	0.835	**0.886**	0.872	**0.862**	**0.871**
Soil moisture	**0.729**	0.582	**0.676**	0.674	**0.723**	**0.702**
Wetness degree	**0.797**	0.721	**0.765**	0.746	**0.792**	**0.772**

In general, the modified Tarboton's flow distribution performed better than Quinn's method, and a low *h* value yielded the best results. The local slope $\tan\beta$ was found in most cases to be superior to the use of the $\tan\alpha_d$ slope. However, a higher *d* value and the beeline slope distance were best for estimating soil pH and species richness, while $\tan\beta$ and flow path slope distance were best for estimating the hydrological variables.

The results indicate the need to further refine the algorithms. Some calculation parameters could be variable in time or space. The value of cta, for instance, could vary with slope or season and the value of *h* could vary with soil type or slope. The species richness of vascular plants and the pH, however, are not expected to vary seasonally.

The results can be used as guidelines for choosing the best method for estimating different site properties from topographically derived information.

4.2 Paper II

The importance of topography for soil development varies among sites. To investigate topography's variable influence on soil properties and soil development on a larger scale, data on forest soil properties from across Sweden were correlated to topographical attributes. The soil data used were from the Swedish National Forest Soil Inventory (NFSI; http://www-ris.slu.se). The study was narrowed to 4000 sites representing Podzols and Histosols distributed over most parts of Sweden outside of the mountains.

Despite the expected scatter due to heterogeneity in the data set from the whole country, which included data from regions with differing climates, geology, and forest management history, it was possible to find correlations between topographic indices and soil characteristics, even at this large scale.

Several significant correlations between topographic indices and soil properties were found. The thickness of the organic layer increased with TWI and the thickness of the leached E-horizon increased with upslope area. Soil pH in the organic layer increased with TWI, while the C-N ratio decreased. Soil pH in the organic layer was also found to be higher for south facing slopes than for north facing slopes. The ratio between the divalent base cation (Ca and Mg) and the monovalent base cation (K and Na) concentrations in the O-horizon increased with TWI (figure 1). This can be explained by a stronger adsorption of divalent base cations to soil particles at increasing soil moisture content, and monovalent cations are thus leached to a larger degree when a plot is exposed to larger water fluxes (Eriksson, et al., 2005).

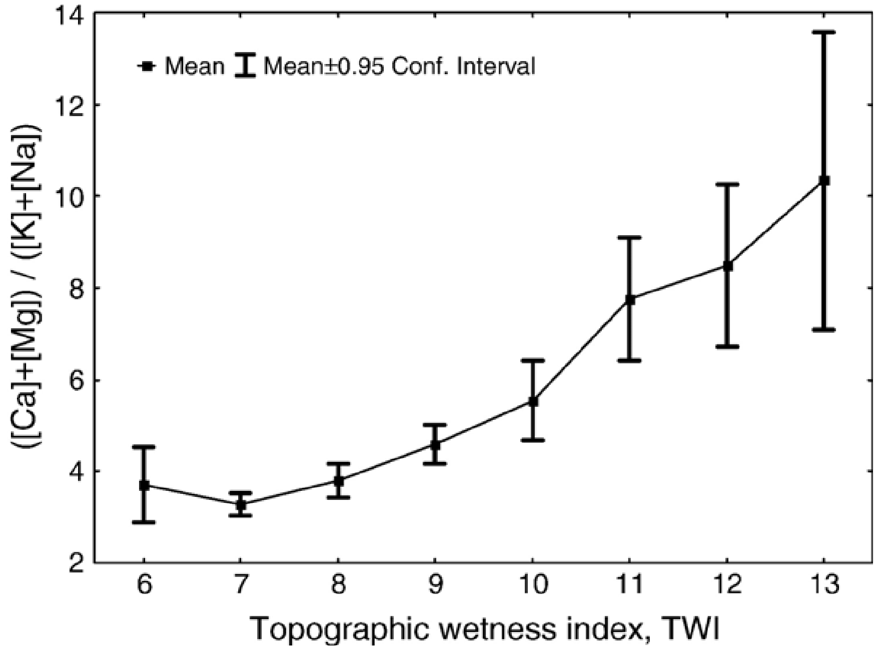

Figure 1. Ratio between the concentrations of the divalent cations (Ca and Mg) and the monovalent cations (K and Na) in the O-horizon for TWI-classes (means and confidence intervals).

The correlations between TWI and pH for the data set covering all of Sweden agreed with correlations found at smaller scales (Zinko, et al., 2005). The value of these results is the larger generality than that of studies using smaller study sites. Our study indicates the potential of topography as an indicator of soil properties but also the need for further studies. Multi-variant approaches might help considering the heterogeneity in the data set which we used by including other variables than topography in the analyses. New data sets covering smaller, and more homogenous, areas with spatially intense observations might be another approach to quantify the importance of topography on soil properties, especially if topographic indices are considered when designing the spatial distribution of sample plots for soil measurements. These correlations confirmed the importance of topography on soil properties, although there was considerable scatter, which could be attributed to heterogeneity in the large data set. The use of topography as a source of information in environmental management is expected to increase in the future, especially as the availability of high resolution elevation data increases.

4.3 Paper III

Two Swedish boreal forest catchments, the 11-ha BS and the 37-ha CC (figure 2), near the village of Balsjö were logged after one and a half years of hourly reference measurements of runoff and biweekly or more frequent stream sampling. The logging took place during March 2006 on a soil covered by a thick snow pack. For another two years the harvest impact was compared to a third catchment, the 20-ha "small" Ref-S, that was left untreated. The data-logged hourly stream water levels were transformed to discharge series using a rating curve which was calibrated using biweekly manual runoff measurements (volume-time method). The runoff change after harvest was assessed by division into three classes of flow rate and into dormant and growing seasons.

After harvest in April 2006 the deep snow pack was covered with tree residues, branches, bark, and twigs, insulating the snow and thus delaying the subsequent spring flood (figure 3). The total amounts of specific runoff were similar from all three sites by the end of July 2006 (approximately 200 mm).

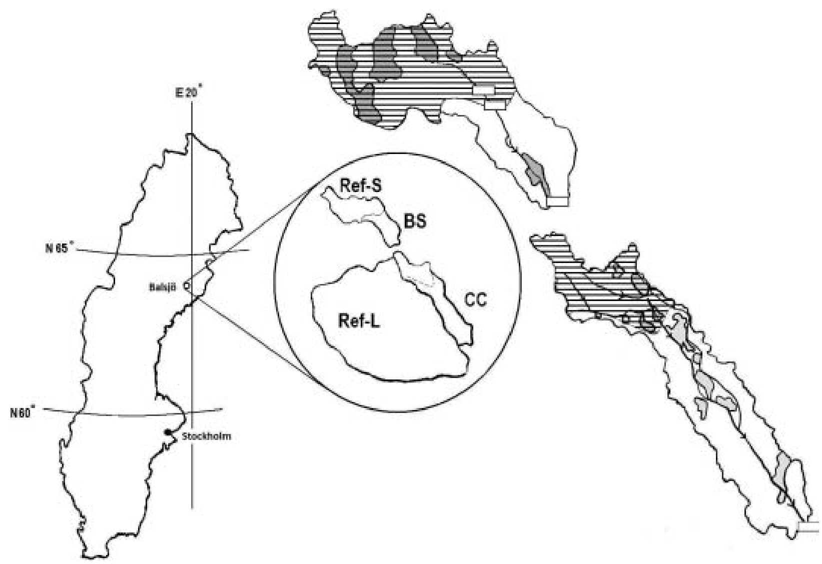

Figure 2. Map of the study catchments and their location in Sweden. The gray areas indicate wetlands (none of which were logged), and the hatched areas indicate other areas that were not logged.

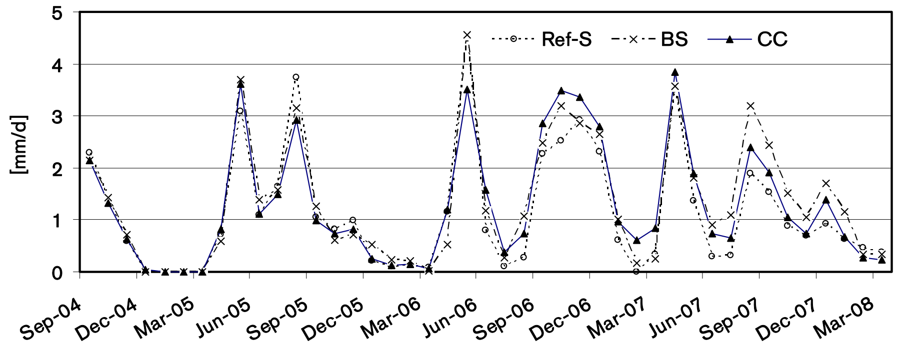

Figure 3. Monthly mean flows from the reference catchment Ref-S, and the harvested catchments BS, and CC.

There was a clear runoff increase during most periods of the two following years. The average runoff increased by 35 % on the two harvested areas relative to the reference area. The increase was more pronounced during growing season (50-70%) as opposed to dormant season (10-30%), and more pronounced at low flow conditions (40-50%) as opposed to high flow conditions (20-30%). During growing season low flow conditions, the increases relative to Ref-S at CC and BS were 60% and 100% respectively. No significant changes were observed during the highest flows (over 5 mm d^{-1}). Since the 2006 spring flood was a special case of the post harvest situation (melt was delayed and attenuated, we hypothesize due to logging slash) there was only the 2007 spring flood to use for statistical analysis. The results showed no significant runoff change during this period (table 2).

To be able to get an idea of the impact caused by flow increase, it is important to consider the extreme events of the flow change rather than the mean changes of flow such as annual flow increase. The large flow increase in the growing season and at low flow conditions is associated with increased ground water levels which in turn can cause a changed pattern in the loss of substances from the terrestrial to the aquatic environment (Kreutzweiser, et al., 2008).

Table 2. The ratio of flow rates from the harvested CC and BS catchments relative to the reference catchment Ref-S before and after harvest. The absolute difference in runoff is noted as millimeters in parentheses. The reference period extended from September 2004 to March 2006. The treatment period started in August 2006 and went to April 2008. Post-harvest change in flow relative to reference area Ref-S divided into seasons and rates (mm in brackets). The period immediately after harvest (April 2006 through July 2006) is not included in these calculations because of delayed snowmelt in the treatment sites. Significant changes (RIA statistics) are in bold. Seasonal changes were not analyzed for statistical significance.

Relationship	CC/Ref-S	BS /Ref-S
Before harvest	96% (535)	101% (557)
After harvest	**136% (956)**	**134% (996)**

Post harvest change	CC	BS
All seasons and rates	**+36**% (254)	**+34**% (253)
Rate < 1 [mm/d]	**+42**% (39)	**+49**% (51)
Rate 1-5 [mm/d]	**+30**% (58)	**+24**% (51)
Rate > 5 [mm/d]	+32% (34)	+19% (23)
Dormant season	+34% (26)	+11% (12)
Growing season	+54% (113)	+68% (138)
Dormant season 0-1 [mm/d]	+36% (15)	+7% (4)
Dormant season 1-5 [mm/d]	+43% (13)	+30% (13)
Dormant season > 5 [mm/d]	n o	N o
Growing season 0-1 [mm/d]	+58% (26)	+99% (40)
Growing season 1-5 [mm/d]	+20% (25)	+21% (28)
Growing season > 5 [mm/d]	+38% (134)	+23% (19)

4.4 Paper IV

In the Balsjö catchment areas stream water DOC concentrations were monitored biweekly throughout the two year reference period as well as two years after harvest (Löfgren, et al., 2009). These samples showed no DOC increase after harvest. In addition to that, high frequency water sampling was conducted in the summer and fall during the second year after forest harvest, in year 2007. Four catchments were monitored of which one reference and two treated areas for discharge. The fourth area was also a reference area (the 320-ha Ref-L, figure 2) but was not subjected to discharge measurements. Its specific discharge was assumed similar to the other reference catchment. The concentrations and transports of DOC for the two treated areas were compared to the two reference sites. This difference between the groups was separated into baseflow and episodes during summer and fall of 2007.

Clear forest harvest effects were observed for both transports and concentrations during both base flows and episodes in the summer period (figure 4). The change decreased towards the autumn where a smaller, but still significant effect was observed for baseflow conditions and no significant effect during episodes.

The result of this study compared with ground water level simulations (see discussion) accentuates the mechanism of higher ground water levels connecting more shallowly situated terrestrial DOC with the aquatic environment, as described by e.g. Bishop et al. (2004), during both episodes and baseflow conditions.

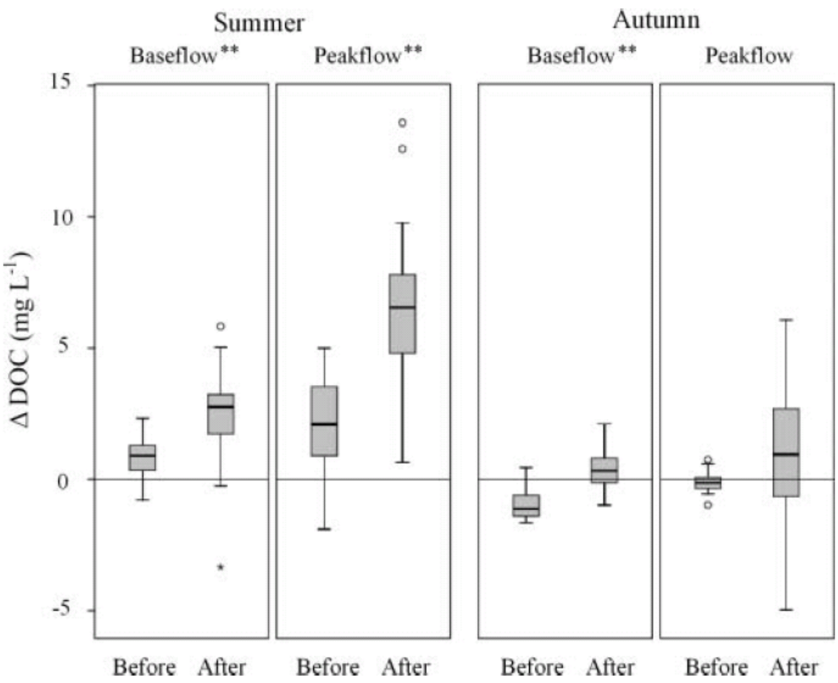

*Figure 4. Box plots of ΔDOC (DOC_H - DOC_C) concentrations for harvested and control catchments before and after the harvesting. Summer is shown on the left, the autumn period on the right. "**" indicates that there was a significant difference between ΔDOC before and after harvesting (according to independent sample t-test with $p < 0.001$), in the size of 2 mg L^{-1} at summer base flow, 5 mg L^{-1} at summer peak flow and 2 mg L^{-1} at autumn baseflow.*

4.5 Paper V

Three of the study streams in the Balsjö study area in northern Sweden were sampled biweekly, site Ref-S (reference site), site North (comprising the reference Ref-S site and the harvested BS site), and site CC (harvested)(figure 2). The sampled chemical properties of most interest for the mercury situation were: total mercury (Hgtot) and methylmercury (MeHg) as well as TOC and suspended matter. During spring flood episodes the sampling was more frequent. The sampling took place during a one year reference period as well as a two year post-treatment period, before the treatment sites were site prepared and replanted in March 2008. This thesis considers the period from harvest to replanting (figure 5).

The Hgtot concentrations increased by approximately 15% and transports by 20-30%. MeHg changes were largely influenced by concentration peaks during summer low flow conditions both before and after harvest. The changes in MeHg concentrations should be interpreted bearing that in mind. Considering the MeHg peaks resulted in a 45% decline in MeHg concentrations from both areas, which to some extent might be explained by a dilution effect of the 35% post harvest stream flow increase.

Leaving out the concentration peaks resulted in no significant MeHg concentration change, but a significant 60% MeHg flux increase from one area but none from the other. The flux estimates were based on linear interpolation among MeHg concentration values, which is a rough estimate that will sometimes overestimate and sometimes underestimate the MeHg fluxes, particularly when the MeHg peaks are considered. The different estimates of MeHg concentration change were made because the low flow MeHg peaks were suspected to be controlled by factors other than the harvest.

For MeHg, concentrations near 1.0 ng L^{-1} and above were only found during flows under ca. 1 mm d^{-1} in the summer. Lower values of MeHg were also found during low flow rates at other periods of the year. At flow rates above 2 mm d^{-1}, MeHg stayed in the range 0.1 to 0.5 ng L^{-1}. There was a positive relationship between flow and Hgtot. At flows higher than 2 mm d^{-1}, Hgtot levels were generally above 4 ng L^{-1}. There was also, generally, a positive relationship between flow and TOC. For suspended matter, there was, in general, a negative relationship to flow, but with a large spread in the actual relationship at flows under 2 mm d^{-1}. As flows increased above 3 mm d^{-1}, the suspended matter concentrations were approximately 8 mg L^{-1}.

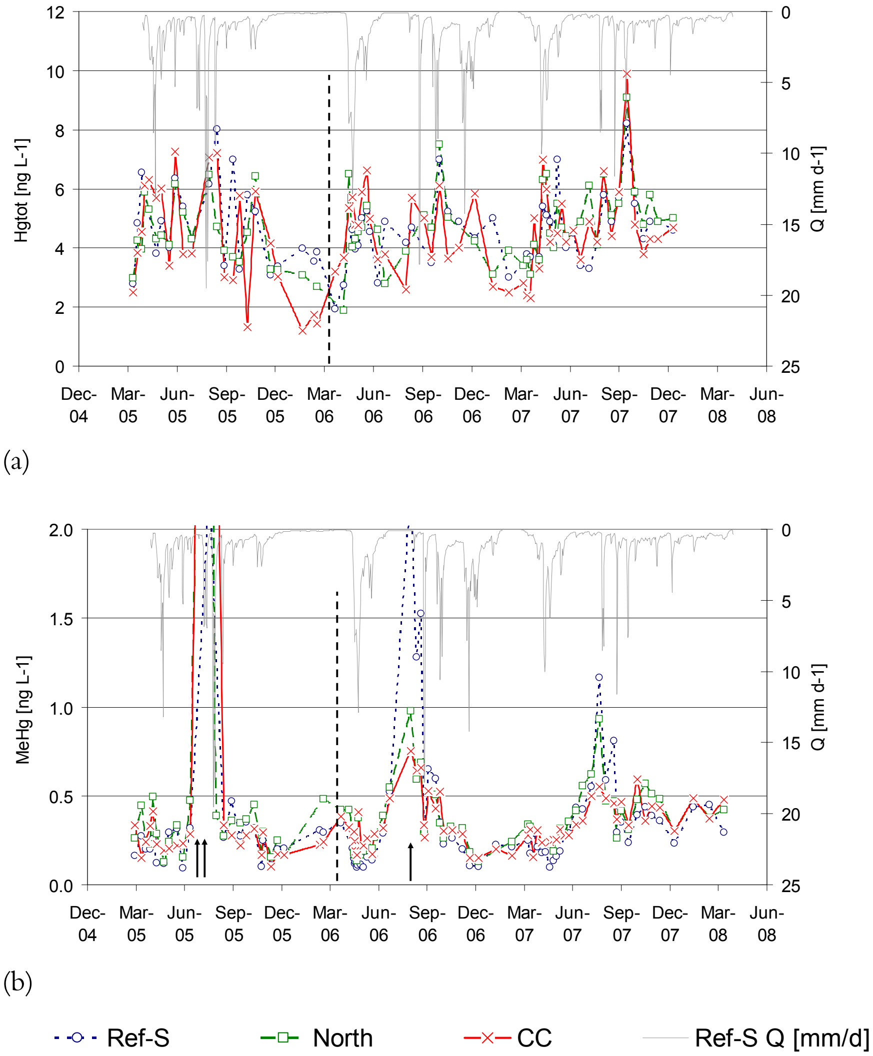

Figure 5. Time series for (a) total mercury and (b) methylmercury in stream water before and after forest harvest. The vertical dotted line indicates the start of the forest harvest operation. ○ Ref-S, □ North, x CC. Discharge, represented by that from the Ref-S catchment, is indicated by the solid line at the top of each diagram. Several values are off the scale for MeHg: at the first arrow, 14 July 2005, North, 3.43 ng L^{-1}; CC, 3.5 ng L^{-1}; Ref-S and BS missing. At the second arrow, 2 August 2005, Ref-S, 2.22 ng L^{-1}; North, 3.75 ng L^{-1}; CC, 5.55 ng L^{-1}; BS, 5.45 ng L^{-1}. At the third arrow, 10 August 2005, Ref-S, 2.22 ng L^{-1}.

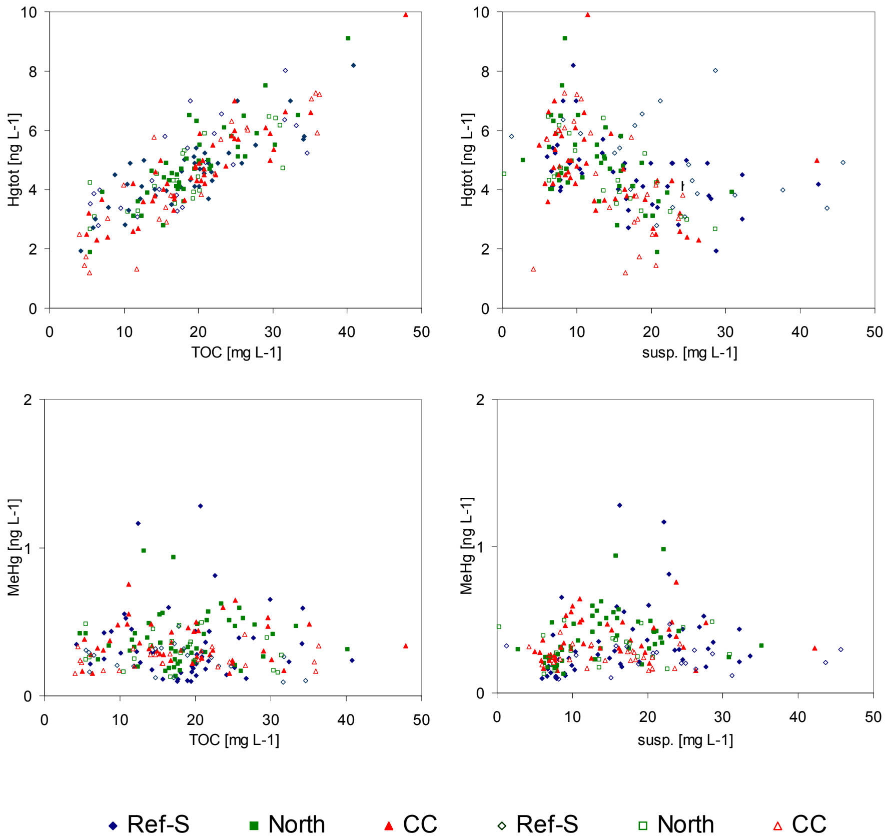

Figure 6. Hgtot and MeHg in relation to TOC and suspended matter for the Ref-S, North, and CC catchments. Open symbols represent pre-harvest samples, filled symbols represent post-harvest samples. Three MeHg observations are off the scale: i) North, 14 July 2005, 3.43 ng L^{-1} MeHg, 7.2 mg L^{-1} TOC, 15.6 mg L^{-1} suspended matter; ii) CC, 14 July 2005, 3.50 ng L^{-1} MeHg, 16.3 mg L^{-1} TOC, 24.2 mg L^{-1} suspended matter; and iii) Ref-S, 10 August 2006, 2.22 ng L^{-1} MeHg, 10.4 mg L^{-1} TOC, 42.4 mg L^{-1} suspended matter.

MeHg did not exhibit a relationship to either TOC or suspended matter concentration (figure 6). Suspended matter concentrations had a weakly negative relationship to Hgtot; indeed the highest suspended matter samples did not have particularly high Hgtot values. The Hgtot concentrations were positively related to TOC. Harvest did not appear to change any of the relationships among MeHg, Hgtot, suspended matter, and TOC.

5 Discussion

5.1 Topography

5.1.1 Topography and scale

The influence of topography on the formation of soils is evident. High correlation coefficients were found between TWI and soil properties both at the spatially restricted sites in northern Sweden as well as in the whole country.

The considerable scatter observed in our study at the national level might be reduced by elevation data with a higher resolution. However, the influence of resolution has been studied by Sørensen and Seibert (2007) who found that while a higher resolution is attractive for a more accurate determination of TWI, higher resolutions might exceed the scale at which the controlling hydrological processes take place, which we also observed in our study.

Different areas have different dominating soil forming factors, which becomes clear in the study covering sites from across Sweden, where there is a much larger variability in the topographical influence on the soil properties measured.

5.1.2 Topography, DOC and Mercury

The topographical influence on moisture and peat thickness, as observed in paper II, indicates that topography is a meaningful indicator for higher concentrations of easily mobilized substances in the soil- and ground water.

Mitchell et al. (2009) found topography to influence the location of methylation hotspots in a Minnesota peatland, by concentrating DOC and sulphate fuelling the methylation processes in the upland-peatland interface.

From our studies on topography we have learned that slightly different hydrological processes control the soil chemistry and the soil moisture conditions. Potential methylation hotspots might be successfully located by not only one topographic feature, but by a combination of topographic tools, to locate areas where both the moisture conditions and soil chemistry conditions are optimal. This might make it possible to create a tool for forest management to avoid soil damage in potential methylation hotspots only, instead of avoiding large zones in the forest where the potential methylation conditions are not as threatening.

A first step on the way could be an application of the model-based wetness index (MWI) created by Grabs et al. (2009) that models spatial distribution of wetlands more accurately than the TWI. A second step could be the location of sites with high upslope contributing areas and to identify interference between the two steps.

5.2 Forestry

5.2.1 Forest harvest and runoff

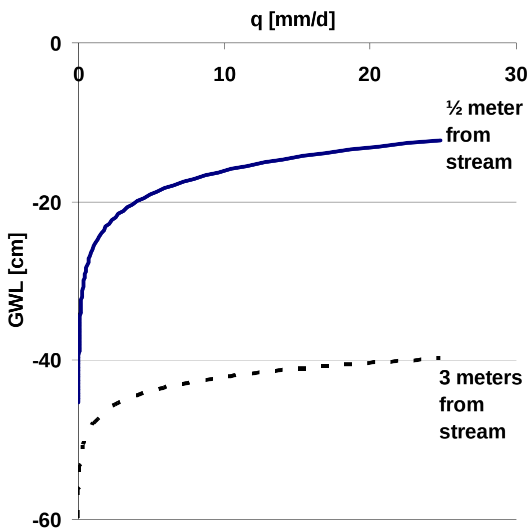

Figure 7. Standard curve of observed relationships between ground water level (GWL) and specific discharge (q) from two locations in the CC site at ½ meter and 3 meters from the stream.

The relationship between ground water level and stream discharge often has an exponential character due to decreased transmissivity with depth. From the relationship between discharge and groundwater level in the Balsjö study area prior to forest harvest, the ground water level was modelled at a number of sites from the post harvest stream water discharge (Vikberg, Manuscript). Figure 7 is a plot of two of these relationships at ½ and 3 meters from the stream.

5.2.2 Forest harvest and runoff – DOC

The results of DOC/TOC change during the entire dormant season was not found significant (paper IV and V). For single periods in the growing season, during both low flow and episode conditions the DOC increased in the harvested areas compared to the reference areas (paper IV).

This DOC concentration increase during growing season is hypothesized to be a result of increased ground water level and more shallow flow paths on the harvested sites during the warm summer months of the growing season. The fact that DOC change was less when flow change was less supports this hypothesis.

The model between ground water level and runoff mentioned above (Vikberg, Manuscript) was combined with the 2007 hydrograph from the reference site as well as a harvested site to model the soil saturation regime at two distances from the stream (figure 8). There is an obvious difference between summer and autumn saturation conditions for the year 2007. This difference is hypothesized to have caused the increased DOC export observed in the summer 2007, diminishing as the autumn progressed (paper IV). That change in ground water level in absolute terms is larger when base flow changes than when peak flow changes, due to decreased porosity and hydraulic conductivity with depth. This, in turn, means that a larger part of the post harvest ground water low flow flushes new soil horizons than at post harvest high flow conditions.

Since the relationship between TOC and Hgtot is so strong (Paper V), one may surmise that the Hgtot concentration and transport also increased during these episodes after harvest.

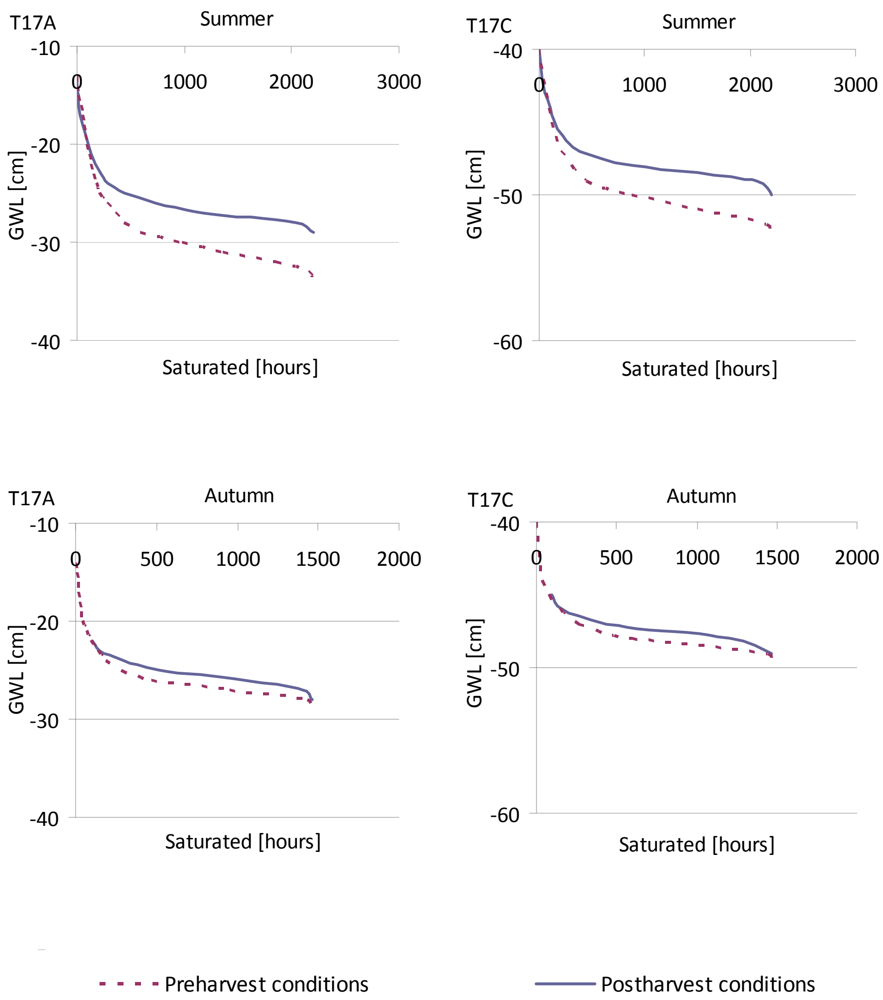

Figure 8. Modeled pre-harvest and post-harvest ground water levels at the harvested site at 0.5 meters (T17A) and 3 meters (T17C) from the stream. The figures are based on preharvest relationships between groundwater levels and runoff, and on 2007 runoff data for the reference Ref-S site and the harvested CC site.

5.2.3 Forest Harvest and Hg - Current knowledge

While Mitchell et al. (2009) found that topography influences the location of MeHg production sites, forestry has been found to cause increased Hg output in boreal forest areas.

The role of forestry for the mercury levels in Swedish freshwater fish has been estimated based on current knowledge (as of 2006)(Bishop, et al., 2009). It estimates that forestry contributes 9-23% of the Hg in Swedish freshwater fish, based on different assumptions, of which one is that forest harvest leads to a doubling to quadrupling of the Hg load to aquatic systems for a decade. These numbers are based on a few existing studies of the Hg-load on aquatic organisms induced by forestry (Garcia and Carignan, 2000; Munthe and Hultberg, 2004; Munthe, et al., 2007; Porvari, et al., 2003; Skyllberg, et al., in press).

The role of forestry is more than above-ground impacts only. In a southwest Swedish forest area, Gårdsjön, a single tractor track caused significant MeHg-concentration increases in a stream for several years (Munthe and Hultberg, 2004). In a recent paper, Skyllberg et al. (in press) suggest that 5/6 of the increase in MeHg load from the terrestrial environment to the aquatic environment is caused by increased methylation and 1/6 is a result of enhanced mobilization. This Hg-load increase can be accumulated in aquatic biota as observed by Garcia and Carignan (1999; Garcia and Carignan, 2000; Garcia and Carignan, 2005), who found Hg-increases in aquatic organisms after forest activity, though these studies did not separate soil damage from tree removal.

5.2.4 Forest Harvest and Hg – Balsjö study

In contrast to other studies (Schuster, et al., 2008) no relationship was observed between MeHg and DOC in Balsjö, either before or after forest harvest. The MeHg dynamics were dominated by lower concentrations during episodes and higher concentrations during base flow, even when some extreme summer base flow concentration peaks were removed. The highest MeHg concentration peaks were observed during warm dry summer months, similar to observations by Schuster et al. (2008), and seemingly triggered by moderate rewetting events as on July 14 2005, August 2 2005, and August 10, 2006 as well as on July 26, 2007. Larger amounts of runoff as during subsequent flow episodes then diluted the MeHg concentration (figure 4b).

Regardless of whether the MeHg summer peaks are included in the analysis, the harvest induced leakage of Hgtot and MeHg from the Balsjö catchment was moderate compared to similar studies. The reason for this minimal response seems to be the conditions at the time of harvest, with a thick snow pack covering and protecting the soil. Additionally, as for the soil forming factor theory, this area might have other factors besides anthropogenic disturbance controlling Hg outputs, i.e the Balsjö area could be less sensitive than other areas to the impacts induced by forest harvest.

According to the Balsjö study it might be possible to mitigate forestry's Hg load by minimizing soil disturbance during harvest. An SFA study, located at the Balsjö site, of a tractor track generated under optimal soil conditions (Bishop, et al., 2008) led to no or modestly elevated soil water MeHg concentration, depending on the interpretation of one set of reference points 3 meters to the side of the track. The interpretation of the SFA results are, however, inconclusive, and more studies are needed on the topic. The SFA study was located outside of the near stream zone.

In another SFA study at the Balsjö site, the near stream zone was impacted at a stream crossing for heavy machinery during harvest. Stream water samples were taken during the post harvest period upstream and downstream from the crossing.

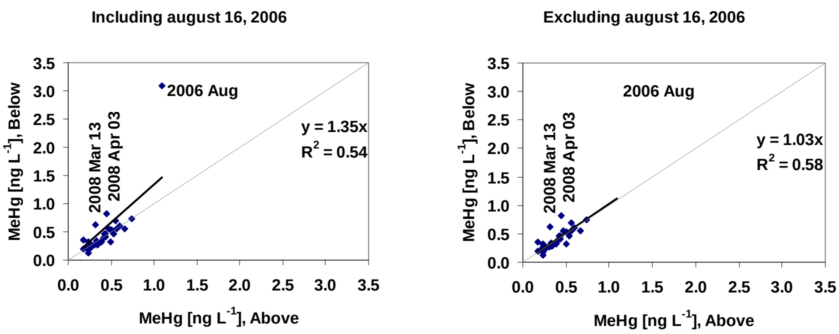

Figure 9. MeHg concentrations above and below stream crossing, including and excluding one extreme summer low flow value

Except for one occasion during a dry summer month in 2006 the stream crossing did not give rise to elevated MeHg concentrations. This exception did not influence the statistical insignificance of the stream crossing on MeHg concentrations (figure 9).

5.2.5 Soil scarification and Hg – Balsjö study

Site preparation by soil scarification would be expected to increase the Hg release to the streams, but the first year of post-scarification data from the Balsjö study area does not show any sign of elevated MeHg concentrations, and only moderate Hgtot concentration increases[1]. Two possible explanations are feasible: i) the Balsjö study area is not sensitive to the

[1] Eklöf, personal communication

disturbance of forestry; or ii) since the soil scarification was limited to the upland soil there was no impact on the potential methylation hotspots.

Consequently, further studies are still needed in order to understand the influence of soil scarification on Hg release.

5.2.6 Forestry and Hg

Forestry has been estimated to generate a 2 to 4 fold increase in output of Hg to the aquatic environment (Bishop, et al., 2009). The impact of the Balsjö forest harvest and soil scarification activities seem to have been mild when evaluating the visible damage in the landscape. Except for one stream crossing (beneath a diverging hillslope that according to Mitchell et al. (2009) is not expected to be a methylation hotspot), the riparian zone has been left undamaged during both logging and scarification.

It seems appropriate to introduce a qualitative measure of disturbance that can potentially be widely acknowledged. This would make it possible to compare the different catchment studies and their conclusions about Hg output related to soil damage, and it would be easier to separate the effect of good forestry practices from a low sensitivity to disturbance among areas.

5.2.7 Mercury in fish

There is still a tendency of increasing mercury content in fish (Åkerblom & Johansson, 2008). While the limits (0.5 mg kg^{-1}) set by the Swedish Food Administration are based on a human consumption perspective, the European Commission has set new limits focusing on the effect on fish consuming birds and mammals. These guidelines are based on studies that observed effect on birds and mammals at levels of 0.2 mg/kg fish. With the usual safety margin set to a factor ten, the proposed EU limit for Hg in fish is 0.02 mg/kg fish. Since the background level of Hg in fish in Sweden is considered to be about 0.2 mg/kg it is impossible for Sweden to live up to the new EU standard. Negotiations are underway to reach a fair level for landscapes, like Sweden[2], that have natural Hg-levels up to 0.2 mg kg^{-1} (Lindqvist, et al., 1991). Verta (1990) estimated natural pike Hg levels up to 0.4-0.5 mg kg^{-1}, based on sediment cores and sediment/organic matter relationship.

5.2.8 Legislation

It is important to put the Hg leakage in a proper perspective. Forestry didn't place the Hg in the forest, but it has to deal with the problem. It is not clear

[2] Johansson, personal comment.

how large the Hg leakage is from entirely unmanaged forests that are not ditched. What has been found, is that wetlands contribute with about as large Hg loads to the aquatic environment as forestry activities do (Bishop, et al., 2009).

SFA recommends different measures that forest owners should take to avoid disturbing the soil in general and the riparian zone in particular, in order to prevent the production and leakage of harmful substances to the aquatic environment. The SFA guidelines for forestry activities are clear but the legislation is blunt and based on the forest owners own knowledge about and interest in environmental issues. Consequently there are few precedents that can be used to guide authorities when it comes to enforcing rules to limit harmful substances in forest runoff (Legislation: Skogsvårdslagen 30§, miljöbalken 12:6§, European Water Framework Directive). As in many other cases environmental considerations are balanced against economic inconvenience. And even if the forest owners are willing to protect the environment more than they must, they also have to make ends meet. Consequently, the interpretation and implementation of the legislation is a political issue, and the question is to what extent the society is willing to prioritize the protection of the aquatic environment to prevent mercury biomagnification in freshwater fish. SFA has been commissioned by the Swedish Government to make a suggestion for implementation of the European Water Framework Directive in current legislation[3]. This is a good opportunity for SFA and the Swedish Government to more clearly regulate and protect our aquatic environment from harmful substances, such as Hg.

5.2.9 Society's perspective

Natural science can contribute to the understanding of mechanisms and processes that give rise to Hg production and leakage. Other scientific disciplines can analyze the costs and benefits of tree harvest in sensitive areas.

From a societal point of view it would be interesting to compare the size of income from biomass harvested in potential methylation hotspots, with the cost of jeopardizing the water quality in low order streams, potentially contributing to Hg-contamination of fish, and fish eating species, among which humans are the top predators.

It seems that *The Tragedy of the Commons* is still an issue of increasing relevance(Hardin, 1968).

[3] Lomander, Swedish Forestry Agency, pers. comment.

6 Conclusions

This thesis clarified that:

- topography influences soil chemistry variations in the landscape
- topographical information can potentially be further developed to increase our understanding of the spatial variability of various biotic and abiotic site characteristics
- a combination of topographical indices could be tested to better explain the distribution of e.g. methylation hotspots
- forestry increased the water yield from the Balsjö study sites, most during growing season and at base flow conditions
- DOC dynamics were influenced by harvest flow increase most during growing season
- increased flow had a first order control on the Hg output
- best management practices might reduce the Hg load to the aquatic environment

This thesis raised the questions:

- are the MeHg summer peaks of significant importance for the aquatic environment or can they be neglected in the large picture?
- does land use influence on the magnitude of the MeHg summer peaks?
- is the Balsjö study area relatively insensitive to harvest and soil scarification in general or were the forestry activities there performed in a way that any representative catchment area would respond so relatively little to?
- would a qualitative measure of disturbance make it possible to more easily compare the impact of forest harvest among studies?

Acknowledgements

Wow – another three blank pages just waiting to be filled with text!
There are a lot of people I would like to acknowledge here in my thesis, so lean back, take a sip of your … erhh … coffee and enjoy the moment – I do!

I was very sceptic to entering the world of PhD studies, well, actually to studies in general. Ten years ago I started my undergraduate studies at SLU, Ultuna, just to take the challenge. I was convinced that I would never enter PhD studies.

But course after course and teacher after teacher managed to catch my interest, and I ended up looking for a master thesis project when an even more enthusiastic lecturer entered the stage. When that lecturer shortly afterwards e-mailed the students if anyone was interested in a master thesis project I didn't hesitate. With that enthusiasm, I found, it might actually be interesting to write a Master Thesis. The lecturer was Kevin Bishop, and the project was Johan Temnerud's PhD project – they needed field workers! But it actually was an interesting project and I did my Master thesis with Kevin, who showed me that science can be exploring unknown land, rather than having to solve difficult problems. Shortly before the master project was over Jan Seibert was looking for a licentiate student and Kevin recommended me. For that I am very grateful, and suddenly I ended up being a PhD student studying the influence of topography. That was the beginning of my PhD-years, this thesis indicates the end of them.

Before my two licentiate years were over Kevin asked me to continue on the newly initiated Balsjö project. The reason I couldn't say no to that is all the good skills Kevin has as a supervisor and colleague:

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