Conceptualizing catchment processes affecting stream chemistry: From basic understanding to practical applications

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Cover: Mosaic of different aspects of this thesis illustrating climate change, forestry, and streams in the Krycklan catchment. (photos: T. Tiwari)

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Abstract

Maintaining good surface water quality is recognized as one of the greatest challenges for future generations. In northern-latitudes, it is predicted that aquatic ecosystems may experience a large climatic change. This could have dramatic consequences for the hydrological cycle, which influences many biogeochemical process and ultimately stream water quality. Additionally, increasing demand for forest resources can increase the pressure on water resources in the boreal forest that already experience large scale industrialized forestry. However, before the combined effects of climate change and forestry on stream chemistry can be understood, the basic principles of how catchments function are first a prerequisite.

In this thesis, investigating the natural variability of stream water quality in a meso-scale boreal catchment showed that temporal and spatial variation in hydrology within catchment landscape types was the main regulator of stream water quality. Shallow groundwater from the dominant landscape types regulated stream chemistry during high and intermediate flows, while large inputs of deep groundwater regulated the chemistry during base flow when the connectivity between landscape types decreased. Additionally, specific landscape attributes reflected different processes occurring in the catchment. By identifying the areal coverage, riparian soils, and connectivity of the catchment landscapes, this work has led to an improved understanding of dissolved organic carbon (DOC), conservative elements, redox sensitive elements as well as those with high affinity for organic matter, and elements derived from atmospheric deposition.

Applying the new conceptual understanding to predict future effects showed that warmer and wetter conditions, as indicated by future climate and forestry scenarios, suggest there may be increased DOC concentrations and fluxes in streams which will be driven by both climate change and forestry effects. Further applications of this new catchment biogeochemical processes understanding to forest management showed that a more cost effective solution for forest management can be achieved by strategically targeting the most vulnerable and sensitive areas of the riparian zone by using a hydrologically adapted buffer zone strategy.

Keywords: Boreal catchment, Water quality, Dissolved Organic Carbon (DOC), Catchment hydrology, Climate Change, Forestry, Riparian buffer zone

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Dedicated to my Family

“Don't tell me the sky's the limit when there are footprints on the moon.”
― Paul Brandt

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 Tejshree Tiwari, Hjalmar Laudon, Keith Beven, and Anneli M. Ågren (2014), Downstream changes in DOC: Inferring contributions in the face of model uncertainties, *Water Resources Research*, *50*(1), 514-525, doi: 10.1002/2013wr014275.

II Tejshree Tiwari, Fredrik Lidman, Hjalmar Laudon, William Lidberg, Anneli M. Ågren, The role of scale, riparian soils and connectivity for predicting stream water chemistry, (*Manuscript*).

III Stephen K. Oni, Tejshree Tiwari, Martyn N. Futter, Anneli M. Ågren, Claudia Teutschbein, José L. J. Ledesma, Jakob Schelker, Hjalmar Laudon, Local and landscape scale impacts of clear-cuts and climate change on surface water dissolved organic carbon in the boreal forests, (*Submitted Manuscript*).

IV Tejshree Tiwari, Johanna Lundström, Lenka Kuglerová, Hjalmar Laudon, Karin Öhman, Anneli M. Ågren, Cost of Riparian buffer zones: A comparison of hydrologically adapted site-specific buffers with traditional fixed widths, (*Submitted Manuscript*).

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The contribution of Tejshree Tiwari (the respondent) to the papers included in this thesis was as follows:

I The respondent was the main person responsible for data handling, data analysis, model development, interpretation, writing, and submission.

II The respondent was the main person responsible for data handling, data analysis, model development, interpretation, writing, and submission.

III The respondent assisted substantially in the model development, interpretation, and writing.

IV The respondent was the main person responsible data analysis, writing, and submission.

Abbreviations

AIC	Akaike Information Criterion
BAU	Business As Usual
BC	Base Cations
DEM	Digital Elevation Model
DTW	Depth To Water
FAO	Food and Agriculture Organization
INCA-C	Integrated Catchment Model for Carbon
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
NPV	Net Present Value
PERSiST	Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport
RCM	Regional Climate Model
RIM	Riparian Integration Model
RMSE	Root Mean Square Error
DOC	Dissolved Organic Carbon

1 Introduction

A prerequisite to ensuring sustainable water quality is the conceptualization of how catchment functions by linking processes occurring at different spatial scales and then translating these understandings to practical uses. However, the fundamental challenge in most efforts are usually focused on the small-scale processes (plots, hillslopes, and small headwater catchments) (Bishop *et al.*, 2008) while management decisions are made at the larger catchment scale.

Predictive modeling offers a solution; however, they are often hindered by the heterogeneity between and within catchments, making scaling up or scaling down catchment processes a challenge. While theoretical understandings about catchment functioning remain a challenge, water resources are continuously threatened by climate change effects and landuse impacts (Watts *et al.*, 2015; Vorosmarty *et al.*, 2000). The challenge lies not only in transferring knowledge from small to larger spatial scales, but also in applying knowledge to real world scenarios in the quest for improving water resource management.

In this thesis, I present an interdisciplinary research which integrates information, data, techniques, and concepts from a number of disciplines to advance the fundamental understanding of stream chemistry in boreal catchments. The understandings and concepts are then applied to advance knowledge of climate change and landuse effects and to improve forest management practices.

1.1 Conceptual overview of the boreal catchment

A catchment can be defined as an area of land that is drained into a central point or an outlet. It is often referred to as a drainage basin or a watershed. Catchments can also be viewed as a combination of smaller subcatchments that are nested into a larger one. A mixture of soil types, vegetation, geology, and topography often combines to create diverse landscapes with intricate stream networks. Boreal catchments, for instance, consists of a mosaic of wetlands, lakes, and forest landscapes (Figure 1). The landscape types also have a first order control on stream water quality (Soulsby *et al.*, 2004; Uhlenbrook *et al.*, 2004) mainly due to the chemistry that are mobilized into streams. The distinct chemical signatures within each landscape are a result of a number of processes such as adsorption and desorption, precipitation and dissolution, complexation and decomplexation, diffusion and decomposition which occur in the soils. For instance, the boreal forest soils consist of a thin layer of organic soils overlaying mineral soils while wetlands are dominated by organic soils. Decomposition of the organic soil and weathering of mineral soils are the dominant processes that give streams their chemical signature. Many of the biogeochemical reaction are controlled by both anaerobic and aerobic processes as well as by pH, creating the chemical signature in streams.

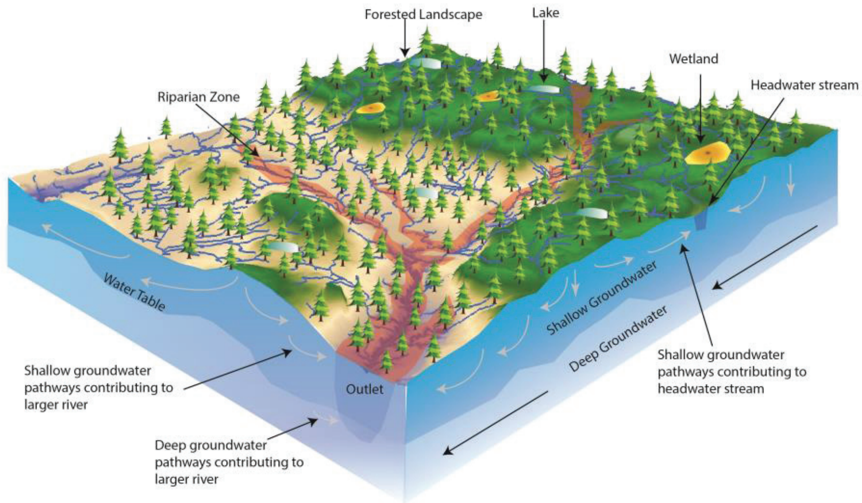

Figure 1. Conceptual view of the components in the boreal catchment and the interaction of shallow and deep groundwater flow paths (Not drawn to scale)

The organization of these landscape types also result in dynamic and complex hydrology which varies depending on seasonality, flow conditions, and stream size (Laudon *et al.*, 2007). Particularly, in the study catchment, the hydrology is dominated by snowmelt during the spring and early summer when up to 50% of the total annual yield is supplied. In boreal catchments, inputs through precipitation (rainfall or snowmelt) become runoff as overland flow or percolated into the soil where it is partitioned into shallow or deep groundwater flow pathways. In the soil matrix, water interacts with organic and minerogenic materials while moving through flow pathways primarily controlled by landscape topography. This creates distinct water chemistry depending on the residence time of water in the catchment, the subsurface environments water encounters on route to the stream and the order of these environments. When flow paths converge, headwater streams are formed. These small streams integrate, transforms, and transmits the landscape signatures from small upstream headwaters to larger rivers downstream. In the downstream, deep groundwater also contributes to stream flow. This deep groundwater often has a distinct chemistry compared to the shallow groundwater as they have longer residence time in the catchment (Peralta-Tapia *et al.*, 2015). As such, the mixture of shallow and deep groundwater is important for both sustaining stream flow and for regulating stream water chemistry.

Bordering the stream network is a narrow strip of land, called the riparian zone which provides the interface between the aquatic and terrestrial environment. The heterogeneous landscape in the riparian zone is created from local and catchment scale variation in topography. The local undulating topography in the riparian zone creates wet areas in gentle slopes when shallow groundwater is near the surface. Catchment scale variation in topography also causes convergence of flow paths in the riparian zone which creates groundwater "hotspots" (Kuglerová *et al.*, 2014b). At these groundwater "hotspots", the moisture levels in soils are higher due to groundwater discharges compared to the non-discharge areas. During higher discharge periods, these groundwater hotspots may form intermittent streams. Wet areas and groundwater "hotspots" creates a unique environment in the riparian zone which fosters high species diversity and creates a site for biogeochemical processes. As such, they have important functions for regulating stream water chemistry (Grabs *et al.*, 2012) as well as providing habitats for biodiversity (Kuglerová *et al.*, 2014b).

1.2 Stream water quality

Surface water quality provides many essential services to society including drinking water, food, and recreation. Since streams are created from the drainage of the catchment landscape, the quality of stream water reflects the hydrological and biogeochemical characteristics of the landscapes. As such, the stream water quality comprises of a multitude of dissolved and suspended materials which varies naturally depending on the landscape types and seasonality (Ågren *et al.*, 2013).

Organic carbon is a particularly important component in boreal stream water quality which contributes significantly to the global carbon budget. It is exported from wetlands and organic rich, mostly riparian, forest soils in the form of dissolved organic carbon (DOC) and particulate organic carbon (POC) (Hope *et al.*, 1994). Naturally occurring DOC comprises largely of fulvic and humic acids which are responsible for the watercolor. While litter and humus decomposition in the forest soils supplies streams with DOC consisting of higher levels of labile low molecular weight (LMW) carbon, wetlands DOC are of higher molecular weight (HMW) and more recalcitrant. Decomposition of these litter and humus are a function of soil temperature and moisture content which in turn strongly depends on climatic factors such as temperature and precipitation, as well as nutrient supply rates. In the boreal forest landscapes, peat accumulation in the riparian zone and wetlands are the most important sources of stream DOC. .

DOC plays an important role in a number of biogeochemical processes in stream water. This includes acting as a strong complexing agent for metals (iron, copper, aluminum, zinc, and mercury) by affecting their solubility, transport, and toxicity (Weiske *et al.*, 2013; Palmer *et al.*, 2005). DOC also affects the transport organic pollutants (DePaolis & Kukkonen, 1997), contributes to the acidity of surface waters, pH-buffering (Hruska *et al.*, 2003) as well as providing a source of energy for stream ecosystems (Jansson *et al.*, 2007). Additionally, DOC is a sensitive indicator for environmental changes.

Stream water also consists of a wide range of other dissolved and suspended materials which are derived from the weathering of bedrocks or from atmospheric deposition. Although many of these elements have important functions for the ecosystem, there are a few which poses a threat to water quality depending on the concentrations and forms. As such, problems of brownification of water (Sarkkola *et al.*, 2013; Kritzberg & Ekstrom, 2012), mobilization of toxic stream chemistry such as Mercury (Hg), Arsenic (As) and Aluminum (Al) (Weiske *et al.*, 2013; Palmer *et al.*, 2005) can pose a threat to stream water quality. Interest in understanding the sources and controls of stream chemistry in the catchment has therefore increased in an attempt to better sustain water quality. Additionally, alteration of the landscape by landuse practices such as forestry as well as effects of climate change has the potential to exacerbate these water quality issues.

1.3 Climate change effects on water quality

Adaptation to climate change is a rising global issue as increases in temperatures and changes in precipitation amount and pattern creates new vulnerabilities for ecosystem services. The IPCC (2007) defines climate change as a statistically significant long-term change in the mean or variability of the earth's climate. The rise in average global air temperature, ocean temperature, shifts in precipitation, melting of artic ice sheets and consequently sea level rise are all indicators of climate change over the past 1000 years (IPCC, 2013). These will have major impacts on ecosystem services in the next 100 years, particularly in the northern latitudes.

The current weather situation exerts an important control on stream water quality (Groffman *et al.*, 2012; Mitchell *et al.*, 1996), therefore systematic changes in the long-term weather, e.g. climate, could also affect the water quality. Since climate change affects both processes in the forest and the aquatic ecosystem, the production and mobilization of DOC from landscape to streams will be affected as warmer temperature and increase in runoff occurs. For instance, increase in temperature and carbon dioxide will increase the net primary production (NPP) through increased photosynthesis (Jansson *et al.*, 2008; Kleja *et al.*, 2008) as climate change causes the lengthening of the growing season and shortening of the winters (Jansson *et al.*, 2008). Higher rates of photosynthesis can increase litter production and soil organic matter which occurs when the NPP exceeds the rate of organic matter mineralization.

Similarly, in the aquatic realm, the increase in temperate and runoff from the landscapes can increase DOC concentrations in streams. Higher temperatures can also increase loss of labile DOC in larger stream network via photomineralization or biodegradation (Jungqvist *et al.*, 2014; Koehler *et al.*, 2014) particularly because the recalcitrant DOC types may become more available by changing the physicochemical properties change (Kothawala *et al.*, 2014). Warmer and wetter conditions can favor production of humic-like carbon compounds which are more effective at absorbing solar radiation and may increase photodegration (Larson *et al.*, 2007). Similarly, there may be higher carbon mineralization and CO_2 evasion of labile DOC from streams (Cory *et al.*, 2014).

Effects on water quality have already been noticed particularly in the boreal catchments where higher concentrations of DOC have been observed across large areas (Oni *et al.*, 2014; Erlandsson, 2008). This increase in stream water DOC has been attributed to increased decomposition of peat soils as a result of warmer temperature (Lepisto *et al.*, 2014) as well as changes in hydrological flow regimes (Holmberg *et al.*, 2014; Wilson *et al.*, 2013; Brooks, 2009). Higher DOC concentrations in stream water is not only alarming for the global carbon budget but also poses a human health issue since higher DOC increases the formation of potentially dangerous chemical by-products through chlorination in water treatment (Gonsior *et al.*, 2014; Lavonen *et al.*, 2013) and mobilized potentially toxic heavy metals into streams. The increase brownification due to DOC not only increases water treatment cost, but also poses a threat to the aquatic biodiversity by changing food web structures.

While climate change continues to be a threat to water quality, future changes could potentially exacerbate existing problems. Even though there are several climate and biogeochemical models that predicts climate change effects at different spatial scales, they all include large uncertainties. Additionally, these models are often not linked, and small-scale understandings are seldom transferred to larger scales.

1.4 Forestry effects on water quality

Approximately 30% of the world's land surface is covered by forests which encompass most of the terrestrial biodiversity on the planet; and provides critical ecosystem services, such as climate regulation and protection of soil and water resources (FAO, 2010). Forests also play an important role in the economies of many countries, particularly in the boreal regions by contributing significantly to the Gross Domestic Product. In Sweden for instance, approximately 70% of the country is covered with forest which accounts for 3000 million m^3 of total standing stem wood volume. Sweden's forestry sector contributes 2.2% to the Swedish Gross Domestic Product and 11.7% to the production sector (Swedish Forest Agency, 2012).

Forestry in Sweden is primarily implemented through a silvicultural practice which is based on clear cutting. Clear cutting is basically the removal of all trees from a limited area with relatively homogenous trees, called a stand. While clear cutting is an economically efficient method of forest harvesting, it is known for affecting local climatic conditions by reducing evapotranspiration, increasing runoff, and soil temperature (Schelker *et al.*, 2013). Consequently, biogeochemical processes and flow paths are affected which leads to increase leaching of dissolved nutrients including DOC for a number of years after harvesting (Lofgren *et al.*, 2009). Industrialized forestry is expected to grow in many countries due to increasing demands for forest products which is used in bioenergy to meet green energy targets including the EU Renewable Energy Directive (Egnell, 2011). With the constant pressure for forest resources to fulfill growing demands, intensive forestry practices aimed at increasing production in the future could have increased impacts on water quality, particularly on DOC. However, much of these effects remain largely unknown.

Currently, efforts made towards developing sustainable forest management practices focuses on tree retention strategies such as riparian buffer zones. Riparian buffer zones are vegetated zones around waterways where harvesting is restricted (Trenholm *et al.*, 2013; Thorell & Götmark, 2005; Lee *et al.*, 2004). The most common approach is to use a fixed width buffers around waterways (Lee *et al.*, 2004). This approach is simple and easy to implement, however often neglect or offer limited protection to areas of high ecological significance in the riparian zone. As mentioned in section 1.1, the riparian zone consists of heterogeneous landscapes with uneven distribution of flow. As such, not all parts of the riparian zone are equally effective at removing pollutants (Tomer *et al.*, 2003), acting as a site for biogeochemical processes and biogeochemical hotspot (Kuglerová *et al.*, 2014a; Kuglerová *et al.*, 2014b). Many scientists therefore proposed that buffer zones should be designed using a variable width which would account for the site-specific conditions based on the physical dimension, topography, and soil types (Qiu *et al.*, 2009; Vidon & Hill, 2004).

One solution is to use high-resolution digital data which identifies site-specific conditions in the riparian zone. Specifically, using digital elevation models (DEM) provides detailed landscape analysis so that wet area mapping and the identification of groundwater hotspots can be possible. One way of mapping the wet areas is to use the depth-to-water (DTW) index (Ågren *et al.*, 2014a). DTW is a measure of the depth down to a conceptual groundwater surface, assuming that gravity and topography control water movement and flow paths (White *et al.*, 2012; Murphy *et al.*, 2011; Murphy *et al.*, 2009). Riparian zones created with a variable width are wider around wet areas and groundwater hotspots to protect the ecological/environmental functions and narrower in drier areas. A key question for applicability is how costly hydrologically adapted buffer zones are compared to those created using traditional fixed width approaches.

1.5 Modeling stream chemistry

Modeling presents an opportunity to investigate the sources and controls of stream chemistry in the catchment as well as to simulate future impacts of climate change and forestry. The perceived benefits of predicting stream chemistry variability at different spatial and temporal scales goes beyond the need for reducing extensive field sampling and costly laboratory analysis. It provides an opportunity for simulating realistic scenarios so as to better aid decision makers in creating sustainable management strategies in sight of threats from climate change and forestry practices.

The heterogeneity at different catchment scales caused by the large variability in precipitation, geology, soil, vegetation, land-use, etc. makes it challenging to use generalization approaches to predict stream chemistry (McDonnell *et al.*, 2007; Beven *et al.*, 1988). One solution is to use chemical mixing models which are based on the assumptions that well-mixed runoff components can be identified with distinct differences in chemical composition and that the runoff components mix conservatively. This enables processes to be up-scaled by transferring knowledge from smaller scale to larger scales through the identification of dominant processes instead of detecting all small-scale variability and complexity (Sivapalan, 2003; Bloschl, 2001).

One way of explaining the scale dependence in the catchment is to use the hydrological connectivity of the landscape to streams which changes both spatially and temporally. Hydrological connective landscapes activate source areas and enables the mobilization of elements to streams along flow pathways. During high flow, the entire catchment is hydrologically connected and all landscapes contribute to stream chemistry. However, during baseflow when the flow reduced, some parts of the landscapes are not connected to the stream network and stream chemistry is consequently affected. Similarly, streams in small headwater catchments are mostly fed by shallow groundwater. As such, by using headwater chemistry as landscape end-members, stream chemistry can be predicted by simply mixing headwater signals in proportion to their areal coverage (Laudon *et al.*, 2011). This approach was particularly successful at the small headwater scales simply because it represents variability caused by the shallow groundwater pathways. However, other processes can be used to explain the variability in stream chemistry in larger scale catchments as shallow groundwater influences are reduced and flow conditions changes.

The hydrological connectivity and riparian soils in the landscape are also other ways to represent landscape variability other than the areal coverage. This includes identifying the riparian areas and the connectivity of the landscapes to streams by a measure of the landscape distance along the flow path to the stream. The riparian soils are hotspots for biogeochemical processes while flow paths are the means by which elements from landscapes are mobilized into stream network. Therefore, classifying the landscape into different landscape attributes (areal coverage, wet riparian soils, and connectivity) can improve the understanding of how diverse elements are affected by different variability in the landscape.

1.6 Ensemble modeling of stream water chemistry

With the awareness of changes in hydrology and temperature caused by climate change and forestry, there are increasing concerns of how water quality will be affected at larger catchment scales where management decisions are based. While there are a number of models which predicts water quality effects at either the small hillslope scale or slightly larger landscape scales, there still remain questions of how these effects are integrated and transformed to a larger scale.

It may not be possible to determine which model represents the reality of the future; however, using an ensemble approach can highlight a range of different outcomes. With each model representing processes operating at a specific scale in the catchment, linking the models can help to translate understanding from one scale to another and ultimately help to gain a more holistic overview at larger spatial scales.

1.7 Research objectives

The overall goal of this thesis was to improve the understanding of how catchments regulate stream chemistry at different spatial scales and apply this to predict water quality changes and improve management practices (Figure 2). These goals were achieved in the following objectives:

1. To determine the landscape's role in regulating stream chemistry (PAPER I & II)
2. To show the importance of hydrological control on stream water chemistry at different spatial scales (PAPER I & III)
3. To determine the effects of future climate change and forestry practices on water quality (PAPER III)
4. To estimate the cost of retaining buffers zones using new methods for protecting surface waters (PAPER IV)

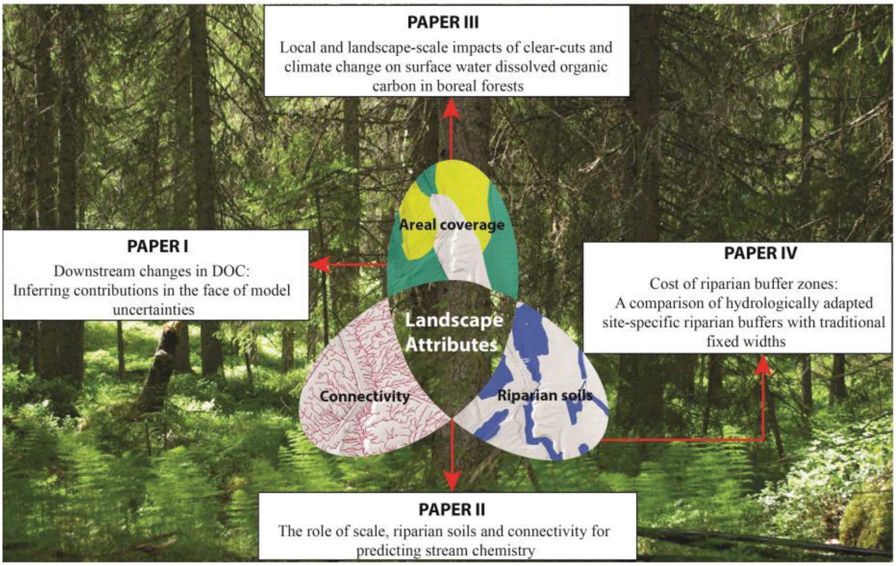

Figure 2. Linking different landscape attributes to advance the understanding of natural processes, future conditions, and human impacts on the catchment.

2 Methodology

This thesis bridges the gap between theoretical understanding of the catchment and practical applications to real world scenarios by dividing the research into two general sections. The first section (2.5) was aimed at understanding how a boreal catchment functions in regulating stream chemistry. The second section (2.6) applied these catchment understandings to gain insights into climate change and forestry effects on water quality and to gain knowledge of an improved forest management practice.

2.1 The Krycklan catchment

The study was carried out in a meso-scale boreal catchment called Krycklan which is located in northern Sweden (Figure 3). It consist of 6790 ha which is divided into 115 nested subcatchments varying in sizes from 4 to 6758 ha [Laudon et al., 2013]. The main landscape types within these subcatchments are mires (0%-76%) and forest (4-100%). Subcatchments in the upper parts of Krycklan are dominated by unsorted till while postglacial sediments dominate in the lower subcatchments (Figure 3). The postglacial sediments mostly consist of a postglacial delta with sandy and silty layers. Underneath the sorted sediments, parts of the Vindelälven esker passes through the main valley of the catchment. The soil mineralogy consist of quartz (31-43%), plagioclase (20-25%), K-feldspar (16-33%), amphiboles (7-21%), muscovite (2-16%), and chlorite (1-4%) (Ledesma *et al.*, 2013).

Climatic conditions can be described by long winters and short summers with a mean annual precipitation of 612 mm. Snow accounts for approximately 40% of the annual precipitation and snowmelt begins approximately in mid-April. The temperature has an annual average of +1.7 °C with an average minimum in January of −9.5 °C.

The forest within the catchment consists of *Pinus sylvestris* (63 vol %), *Picea abies* (27 vol %), and deciduous forest stands (10 vol %). Although the forests are second growth forest, 90% are classified as productive (Figure 3). As such, forestry is the dominant land use within the catchment with small portions of low intensity agriculture (1%).

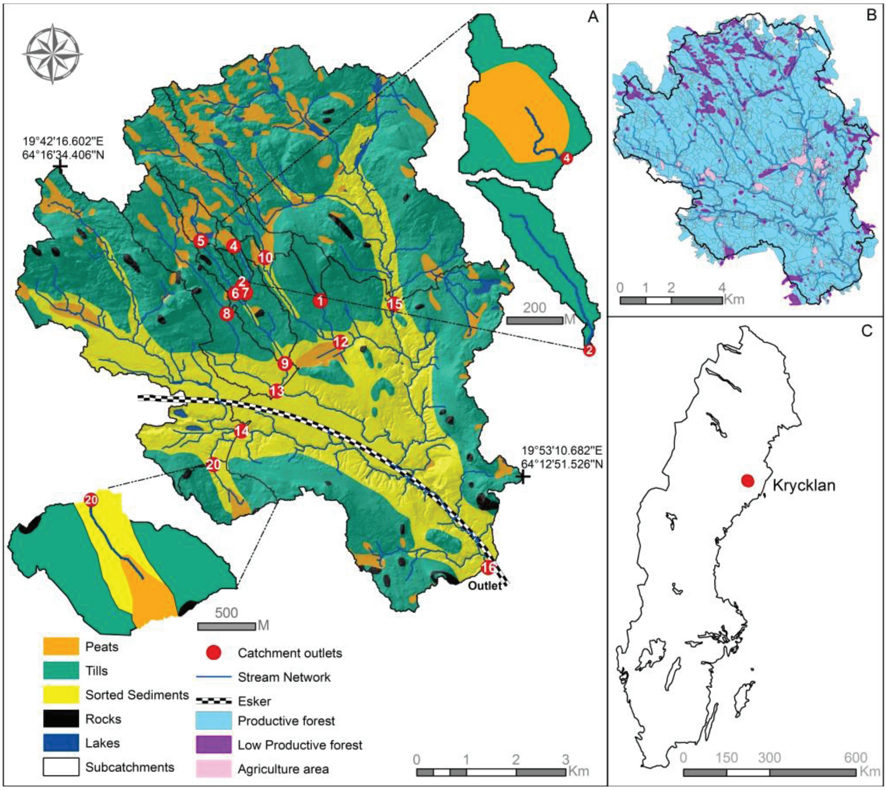

Figure 3. Map of study area showing subcatchments used in the study, landuse and landscape types. A) Subcatchments, quaternary deposits, B) 1751 forest stands divided into productive forest area, low productive forest area, and agricultural areas, C) location of study catchment in Sweden.

2.2 Stream water sampling

From 14-monitored catchments, water samples collected from three first order streams (C2, C4, and C20) (Figure 3) were used to create a model of DOC at the catchment outlet (C16) using four years of data (2006 - 2010) (Paper I & III), while samples from all 14 catchments were used in modeling the variability of 34 elements (Paper II). Sampling frequency varied seasonally depending on discharge conditions with more frequent sampling (3-4 times per week) during the spring flood, fortnightly sampling during average flow conditions, and monthly sampling during winter baseflow.

All samples were collected in high-density polyethylene bottles which were previously acid washed and rinsed with stream water three times before collection and subsequent +4° C and dark storage. Analysis for DOC was done using a Shimadzu TOC-V_{PCH} analyzer after the samples were acidifying to remove inorganic compounds. Major elements were analyzed using ICP-OES (Varian Vista Pro Ax) while trace elements were analyzed using the ICP-MS (Thermo Xseries 2) (see (Lidman *et al.*, 2012; Buffam *et al.*, 2007) for further details).

2.3 Discharge measurements

Discharge data was obtained from two catchments which were measured using different techniques. In the smaller headwater catchment (C7), a 90^{o} V notch in a heated weir house with a pressure transducer connected to a Campbell Scientific data logger was used to determine stage height (Paper I, II, & III). Discharge at the Krycklan catchment outlet was determined using an OTT RLS radar level sensor located above the surface of the stream (Nathanson *et al.*, 2012) (Paper I). Daily discharge was determined based on rating curves for each site, and created from hourly measurements of water level heights.

2.4 Digital terrain analysis

Light detection and ranging (LIDAR) were used to create high-resolution digital elevation models (DEM) (5 m resolution for Paper I, 2 m resolution Paper II). The DEM was then used to delineate watersheds, create stream networks, identify wet areas and groundwater hotspots. All analysis was done in ArcGIS (versions 10.0 and 10.2) by first making a flow compatible model which included “burning” ditches across roads and filling depression before any landscape analysis. Flow direction and flow accumulation rasters were created using the D_8 algorithm (Jenson & Domingue, 1988; Ocallaghan & Mark, 1984). From this, a 16 ha flow initiation thresholds was used to create the perennial stream network. An upstream flow length raster was also created from the flow direction model (Paper II).

The dominant quaternary deposits (here after referred to as landscape type) within the catchment were determined using the quaternary deposits map (1:100,000) from the Geological Survey of Sweden (SGU Uppsala, Sweden) to create polygons of till, peat, rocks, sorted sediments and lakes within each subcatchments (Ågren *et al.*, 2010). These polygons were used to estimate the areal coverage of each landscape type (Paper I, II, & III).

2.5 Modeling stream chemistry

To determine the sources and controls of stream chemistry, and how these changes as streams move from small headwater catchments to the larger catchment outlet, two sets of modeling approaches were used. In the first approach, the role of landscape types, instream processing and hydrological pathways in regulating DOC stream concentrations was investigated. In the second approach, I further investigated how different landscape attributes affect the variability of a wider range of diverse stream chemistry.

*Figure 4.*Streams and landscape elements used to model stream chemistry. A) Small forested headwater draining till soils, B) Wetland landscape type, C) Confluence of streams draining different landscape types (dark, high DOC stream draining wetland to the right and more transparent, low DOC, stream draining sorted sediments to the left), D) Larger downstream river.

2.5.1 Modeling DOC (Paper I)

Three steps were used to investigate DOC variability in the Krycklan catchment. In the first step, the influence of shallow groundwater on DOC was investigated using a landscape-mixing model. In this step, headwater catchments of the dominant landscape types (Peat, Tills, and Sorted Sediments) (Figure 4) were used as end-members and mixed in proportion to their areal coverage to predict the DOC concentrations at the Krycklan outlet (Eq. 1).

$$\mathrm{DOC_{Outlet}} = \mathrm{A} \times \mathrm{DOC_{Peat}} + \mathrm{B} \times \mathrm{DOC_{Till}} + \mathrm{C} \times \mathrm{DOC_{Sorted\ Sediments}} \qquad \text{(Eq.1)}$$

Where *A, B* and *C* represents the areal coverage of the Peat, Tills and Sorted Sediments (in proportion), while DOC_{Peat}, DOC_{Till} and $DOC_{Sorted\ Sediments}$ represent the DOC concentrations (mg L^{-1}) measured at headwater end-member catchments outlets (C4, C2, C20 respectively) (Figure 3).

The second step showed how instream processes affected DOC as it moves from small headwaters to the catchment outlet. This was determined by calculating the quantity of DOC consumed by bacterial degradation and transformed by photo-oxidation based on laboratory-derived relationships (Berggren *et al.*, 2010; Köhler *et al.*, 2002), then deducting this from the modeled DOC in the first step.

In the third step, the influence of changing hydrological pathways was investigated using a mass balance of base cations (BC) fluxes and the comparison of specific discharge. In this step, it was assumed that the concentration at the catchment outlet was a result of the mixture of shallow and deep groundwater pathways. As such, any gain or loss in the surface concentrations was quantified using deep groundwater based on mass balance. To further support the idea of deep groundwater contribution to the stream, a comparison of specific discharge from a small headwater catchment (C7) was made with that of the Krycklan outlet (C16) (Figure 3). Larger differences in the quantities of specific discharge at the Krycklan outlet compared to the headwater catchment were assumed to be from deeper groundwater source.

2.5.2 Modeling diverse stream chemistry (Paper II)

Since landscape types showed a prominent role in determining stream chemistry (Paper I), I investigated how three different landscapes attributes (areal coverage, riparian soils, and connectivity) can be used to predict the variability of 34 elements in the 14 catchments. Each landscape attributes represented specific catchment processes occurring at different scales within the landscape.

While the areal coverage model assumed that the size of the landscape was the dominant regulator of stream chemistry, the riparian soils and the connectivity models assumed that landscapes that are more hydrologically connected to streams will have greater influence on stream chemistry. The areal coverage of the landscape type was determined by the size of the polygons as described in Paper I. The riparian soils were determined using wet area mapping based on a depth to water index (DTW) (Ågren *et al.*, 2014b; White *et al.*, 2012) (Eq.2).

$$\mathrm{DTW} = \left[\sum \frac{dz_i}{dx_i} a\right] x_c \qquad \text{(Eq.2)}$$

DTW is the assumed depth down to a modeled groundwater table, calculated using the slope (*dz*/*dx)* of a cell *(i),* cell size (m) (x_c) and a constant (a = 1 when the path crosses parallel to the cell boundaries and 1.414214 when it crosses diagonally). The connectivity of the landscape was determined by the average distance of flow paths to the stream within each landscape type.

A stepwise multiple linear regression analysis was used to first find the best combination of landscape variables (Peat, Till, Sorted Sediments) for each model. Then a comparison of the Akaike Information Criterion (AIC) was used to show the best of the three models for each of the 34 elements. Based on the Akaike weights, the likelihood of the model being the best model was determined.

2.6 Application of models and understandings

With a conceptual understanding of how stream chemistry was regulated in the meso-scale Krycklan catchment, I applied this knowledge to predict how stream chemistry will be affected by future climate and forestry scenarios. Then, I evaluated the economics consequences of an improved forest management technique based on some of this new knowledge.

2.6.1 Modeling climate change and forestry effects (Paper III)

An ensemble modeling approach was used to determine how both DOC concentrations and fluxes will be affected by future climate change and forestry scenarios for the period 2061-2090. The method used was first discussed in Paper I, where DOC signal at the catchment outlet - was predicted using headwater signals as end-members (Eq.1) and corrected for deep groundwater input. Headwater DOC signal from the dominant landscape types (Peat, Till and Sorted Sediment catchments) were modeled using two biogeochemical models which represented processes operating at different scales; the hillslope (Riparian Integration Model (RIM)) and the landscape (Integrated Catchment Model for Carbon (INCA-C)).

While RIM projected DOC based on a number of small-scale parameters, INCA-C projected DOC on a general landscape level using a larger number of parameters. Both models used hydrological data derived from a landscape scale hydrological model (Precipitation, Evapotranspiration, and Runoff Simulator for Solute Transport (PERSiST) which used temperature and precipitation data from 15 Regional Climate Models (RCM). Base on this, a number of possible climate change impacts on DOC at the outlet of the Krycklan catchment was calculated.

First the biogeochemical models were calibrated to reproduce present day climate conditions (called "Krycklan Calibrated" - KC). To simulate the effects of forestry on DOC, present day values (PDF) were first simulated in the Krycklan catchment based on the results of the Balsjö clear cut experiment (Schelker *et al.*, 2013). In general, clear-cutting was found to increase soil temperatures as well as runoff which yielded higher DOC concentrations and DOC exports in draining water. This done by superimposing forestry scenarios on climate change scenario based on clear-cut effects on soil temperature (for RIM), perturbed hydrology from PERSiST and perturbed process rates and carbon partitioning in INCA-C. This effect was then altered to reflect different degrees of clear cut intensity annually where 0% clear cut represented Krycklan Calibrated (KC), 0.86% represented the business as usual scenario (BAU) and 1.72% represent the intensive forest harvesting (IFH). A comparison was then made to see how DOC signals will be affected based on climate change scenarios and forestry alone or combined, to test if climate change and forestry effects interact.

2.6.2 Evaluating new methods for protecting waterways (Paper IV)

Traditional approaches used to protect surface waters from forestry activities are commonly based on retaining fixed width buffer zones around waterways. Fixed width buffer zones although simple to design and implement, have been criticized for not accounting for the spatial heterogeneity of biogeochemical processes and biodiversity in the riparian zone (Richardson *et al.*, 2012; Lazdinis & Angelstam, 2005). Consequently, the variable width buffer zone which adapts to site-specific hydrological conditions and targets areas important for biogeochemical and ecological functions is suggested as a credible alternative (Kuglerová *et al.*, 2014a; Vidon & Hill, 2004). However, little is known about the monetary cost of hydrologically adapted buffer zones compared to the traditionally used fixed width ones.

As such, in this study the DTW index (Eq.2) was used to create a set of hydrologically adapted buffer zones (DTW-index 0.1 m, 0.25 m, 0.5 m, and 1 m) assuming that wet areas represented the riparian zone (as described in Paper

II). These were compared to the most commonly used fixed width buffer zones (5 m, 10 m, 15 m, 20 m, 30 m) which were created using the buffer analysis tool in Arc GIS 10.0. Groundwater "hotspots" (10 m wide and 30 m long) which improves the ecological integrity of the riparian zone were used in combination with both hydrologically adapted buffer zone and fixed width buffer zones when evaluating the monetary cost of retaining trees in the buffer zone.

The evaluations of the cost of leaving the buffer zones unmanaged were done using the Heureka forestry decision support system *(Wikström et al., 2011)*. Heureka is based on tree cover development which is predicted using data on current conditions, applied management actions, and known ecological processes. The current condition of the forest was estimated from LiDAR data (17x17 m resolution). Manual air photo interpretation was used to delineate the 1751 stands in the catchment and to define tree species composition. The mean value of each variable from the pixels within each stand was used in the analyses. It should be noted that the cost calculated does not include implementation cost but just the value of the forest stands within the buffer zone. This was determined by simulating alternative management actions over 100 years for all stands in the catchment which were based on standard management procedures in the region with normal thinning intensity and rotation periods. The alternative with the highest net present value (NPV) was chosen. The NPV represents the present and future forestry activities, i.e., the predicted income minus the cost of future activities (such as thinning and clear-cutting with appropriate regeneration after harvest) from period 1 to infinity discounted back to today with a 3% interest rate.

The cost of the different buffer zones was determined by calculating the reduction in NPV between a simulation without any buffer zone at all and a simulation where the area within the different buffer zone widths were left unmanaged for all scenarios.

3 Results and Discussion

Under the threats of climate and land use change, the world's water resources are constantly being pressured. In order to gain further insights on how water quality might change under the influence of future climate and forestry practices, and to be able to develop sustainable management practices to cope with land use pressures, there needs to be a better understanding of how the catchment function under present conditions.

As such, in this research I used an interdisciplinary approach to show that landscape types and hydrological pathways are the dominant regulators for stream water quality in boreal catchments. Additionally, I have shown that the role of the catchment landscape changes, depending on the reactive nature of the stream chemistry. By using the conceptual understandings of how the catchment functions, the results suggest that both climate change and forestry will impact water quality in the future. Similarly, hydrological understanding can be used as a tool for creating cost effective riparian buffer zone.

3.1 Deciphering catchment functions in regulating stream chemistry

In the attempt of improving the understanding of how boreal catchments regulate stream chemistry, it was found that there neither is a single model to predict stream chemistry variability at different spatial scales nor is there a single reason to explain the variability of all stream chemistry that constitutes the stream water quality. Instead, a combination of interrelated processes changes roles in regulating stream chemistry as catchment sizes, landscape types and hydrological conditions change. This was found by investigating DOC variability in the Krycklan catchment (Paper I) and by using different landscape attributes to predict the variability of 34 elements in stream water (Paper II).

3.1.1 The role of landscapes, instream processing and flow paths (Paper I)

Landscapes play both the role of sink and source for stream chemistry. For DOC, peat in wetlands and riparian soils were the main source of stream DOC (Ågren *et al.*, 2013; Grabs *et al.*, 2012; Laudon *et al.*, 2011). As such, the dominant landscape types explained DOC variability in small headwater catchments (Laudon *et al.*, 2011). However, in larger catchments, where there are additional landscape types (sorted sediments), the variability of stream DOC cannot be easily explained by just landscape types, but the contribution of deep groundwater must also be included.

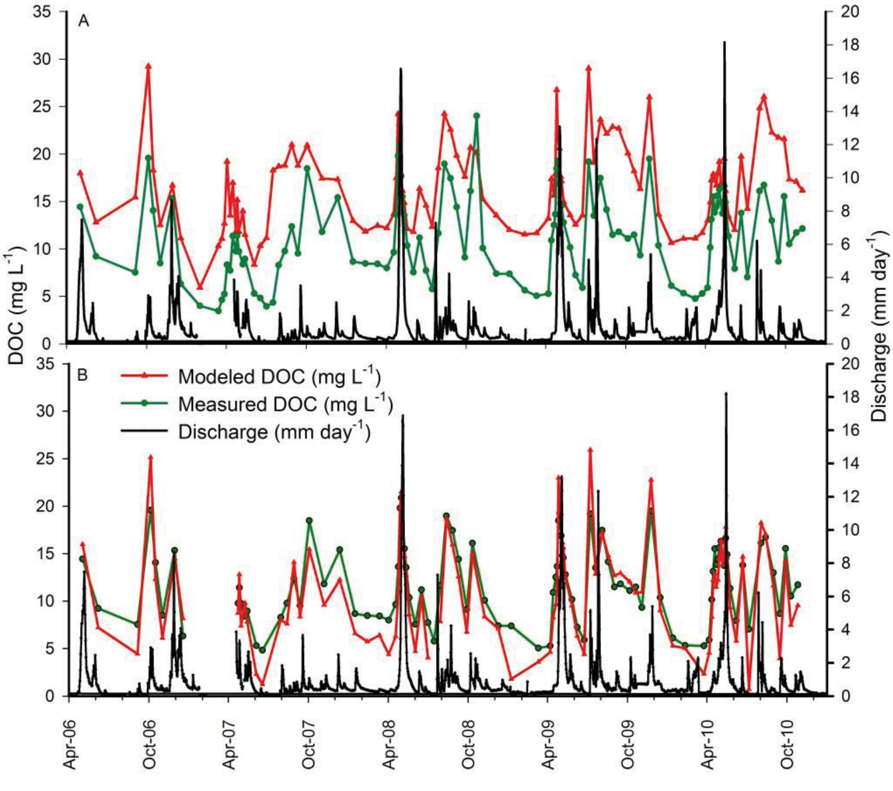

Figure 5. Model of DOC concentrations in the Krycklan catchment showing the improvements from using a three component model and instream processing (A) by including deep groundwater during baseflow (B) (From Paper I).

This was shown by the three-component landscape-mixing model which although predicted DOC well during high and intermediate flow conditions, over predicted during baseflow (R^2 = 0.66, RMSE= 5.5 p<0.0001) in the larger catchment. The success during high and intermediate flows was likely because all landscape types were more hydrologically connected to the stream through shallow hydrological pathways which were well represented using the three component endmembers. However, as the hydrological connectivity between these landscapes decreased during the low flow periods, so did the predictive power of the model indicating the influences of other processes.

Although many have suggested that instream processes has a dominant role in regulating stream chemistry during baseflow due to the longer in channel travel time (Benner, 2001; Tranvik & Bertilsson, 2001; Bertilsson & Tranvik, 2000), it could not explain the over-prediction in the model (Figure 5A). DOC lost to bacterial degradation and photo-oxidation was found to be less than 1 mg L^{-1} day^{-1} and only slightly improved the DOC model fit (R^2 = 0.68, RMSE= 5.2, $p<0.0001$).

However, the addition of deep groundwater input was demonstrated to be a more important variable for explaining DOC during baseflow. Since deep groundwater has a longer residence time in the catchment, it has characteristic higher BC concentrations and lower DOC concentrations than shallow groundwater (Klaminder *et al.*, 2011). During baseflow when the stream flow recedes and the input from shallow groundwater sources is reduced, large quantity of low DOC from deep groundwater diluted the stream DOC concentrations (Peralta-Tapia *et al.*, 2015; Payn *et al.*, 2012; Covino & McGlynn, 2007). This was shown by using two independent approaches (BC as a tracer and comparison of specific discharges) which both indicated that there was up to 80% deep groundwater input during baseflow.

These results are consistent with the findings of others which also highlighted the importance of deep groundwater during low flow (Capell *et al.*, 2011; Wu *et al.*, 2004; Ladouche, 2000). Including deep groundwater improve the overall model fit (R^2 = 0.88, RMSE= 2.2, $p<0.0001$) (Figure 5B). The contributions of shallow groundwater and deep groundwater add new insights to how biogeochemistry is regulated in catchment at these spatial scales. It also provides an additional explanation as to why small streams dry out during baseflow while a larger river continues discharging.

3.1.2 The role of scale, riparian soils and connectivity (Paper II)

The landscapes role has been widely established in Paper I as influencing the stream water quality both biogeochemically and hydrologically. By changing the conceptualization of how the landscape influences stream chemistry, I have shown that a wide range of elements that varies in chemical nature, reactivity, and complexity can be predicted at various spatial scales by targeting specific attributes of the landscape (Paper II).

For instance, if the landscape is viewed as a mosaic of processes that can be represented by the areal coverage, then stream chemistry whose main source are derived from weathering of minerals (Weyer *et al.*, 2014; Klaminder *et al.*, 2011) can be best predicted. This includes the BC and a few others (Cl, Si, Sr, F and S) which can be expected to behave relatively conservative (Liu *et al.*, 2013; Batayneh & Zumlot, 2012). Other more complex elements were modeled less successful with this general approach. This is because the areal coverage approach captured broader scale processes while finer scale processes are needed to explain the more complex elements (McGuire *et al.*, 2014).

Conceptualizing the landscape as a mosaic of wet areas that are hydrologically connected to the stream, improved the prediction of elements with high affinity for organic matter (e.g. Al, Ni, Th, and Y) and some redox sensitive elements (e.g. Mn, U, Se, Sb, Cu and Cr). This is because wet areas produce organic soils where sites for biogeochemistry processes are found and the formation and mobility of elements are favored (Williams *et al.*, 2014; Heckrath *et al.*, 2008). This is a key aspect to note when developing sustainable land management techniques as it targets critical areas (biogeochemical hotspots and areas with high biodiversity) which can be more economical than protecting the entire landscape (Paper IV).

The predictions of DOC and some elements which are highly influenced by atmospheric deposition were best predicted with the connectivity method. This indicates that these elements are more dependent on the location of the source areas rather than the size of the landscape sources (Tetzlaff *et al.*, 2007; Pringle, 2003). The fact that the prediction could be improved in some case, for instance DOC, by this new models indicates that it does not only matter how much, for example, peatland area there is within a catchment, but primarily where in the catchment the peat is located. It is also dependent on how connected are these landscapes to the stream and the dominating hydrological pathways within the catchment.

It is obvious that some elements end up in different groups despite their similarities. I attribute this to the different environmental processes affecting the element. For instance, the variability of S and SO4 were best explained by the riparian soil and areal coverage methods respectively. This can be explained by the difference between the sulfate derived from weathering of sulfate bearing minerals in the soils (SO4) (Mitchell & Likens, 2011) and those from atmospheric deposition (S) (Miles *et al.*, 2012).

3.2 Translating fundamental concepts and understandings to practices

While Paper I and II provides the fundamental understandings of the processes and the functions affecting stream chemistry in the boreal Krycklan catchment, the real strength of these findings lie in their applicability to solve current environmental issues. As such, the conceptual understanding of how DOC is regulated in the Krycklan catchment (Paper I) was used to further model the effects of future climate change and forestry on DOC (Paper III). Similarly, the understanding of the controls on biogeochemistry (Paper II) was used to create hydrologically adapted buffer zones which were assessed for economic feasibility (Paper IV).

3.2.1 Climate change and forestry effects on water quality (Paper III)

To quote Albert Einstein "the future is an unknown, but a somewhat predictable unknown". In this respect, while it is not possible to know exactly the state of water quality in the future, our current understandings of how the catchment system functions and how the drivers of system will change can allow us with some degree of certainty to understand future conditions.

For DOC, understanding how the main drivers (temperature and runoff) will change under different climate change and forestry scenarios paves the way to predicting future conditions at both small and large catchment scales. Based on 15 scenarios of regional climate change models (RCM), the future of the Krycklan catchment appears to be warmer and wetter resulting from increase in both temperature and precipitation. Forestry effects also indicate that soil temperature and runoff will increase as a result of reduced transpiration following clear cutting, until canopy closure is re-established. When this was further simulated through the biogeochemical models (RIM and INCA-C), the local effects on headwater concentrations were predicted.

The responses of the headwater catchments to climate change were different depending on the scale of simulations for each model. When DOC was simulated with the riparian conditions as the main drivers (RIM model), an increase in the headwater DOC signals for all landscape types was observed. However, when simulated assuming that the processes in the entire catchment contributed to DOC (INCA-C model), increases were observed in the forest on till and forest on sediment headwater catchments while a decrease was observed in the wetland catchment. The increases in the forested catchments can be explained by increased mineralization of organic layers in the mineral soils which may contribute to increase DOC availability while the decrease in the wetland was more likely due to dilution following precipitation events. This decrease in DOC signals from wetlands are in contrast to other researches which suggest that DOC concentrations will increase from wetlands due to higher temperature and increase runoff (Pastor *et al.*, 2003; Freeman *et al.*, 2001). An interesting result was that the effects of forestry and climate change on surface water [DOC] are additive at a landscape scale but not at the local scale, where a range of landscape-element specific responses were observed, suggesting complex interactions between forestry and climate change effects in the different landscape elements.

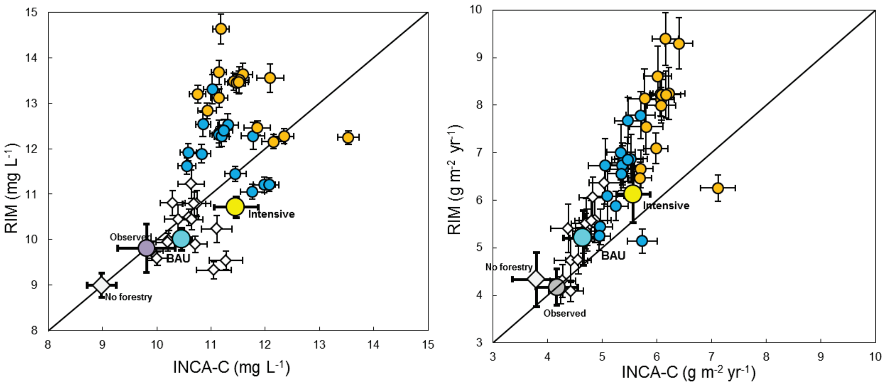

Figure 6. Integrated DOC signal at the meso/large scale as projected by a Landscape Mixing Model under the ensemble of climate change scenarios (white) and climate change plus forestry scenarios (BAU= blue & intensive forestry= yellow). The error bars indicate the inter-annual variation (standard error) in present day (2005-2012) and projected [DOC] and fluxes (2061-2090). The larger symbols represent the present day DOC concentrations and fluxes (white = no forestry; blue = BAU forestry scenario; yellow = intensive forestry) and dark grey represent the observed DOC concentration and flux.

Both biogeochemical models agreed that there will be an increase in DOC concentration in the future regardless of whether the main climatic control on stream biogeochemistry lies in the riparian zone (according to RIM) or in the whole landscape (according to INCA-C), though INCA-C predicted slightly lower concentrations and fluxes than RIM. At the landscape scale I found that, approximately 1 mg DOC L^{-1} in surface waters can be attributed to clear-cuts, both climate change and intensified forestry can each increase DOC concentrations by another 1 mg L^{-1} in the future, which is less than that seen in many waterbodies recovering from acidification.

3.2.2 Evaluating the economics of hydrologically adapted buffer zones (Paper IV)

The demand for timber to meet the worlds growing needs will continue to pressure natural resources, including the soils and water resources which are vulnerable to forest activities. There is a need to improve forest management so as to protect ecological functions while maintaining production goals. Previously, Kuglerová *et al.* (2014a) showed that the riparian buffer zone that are adapted to the hydrological site-specific condition improves the protection of ecological functioning of the riparian zone. Evaluating the monetary cost of this buffer zone in Paper IV showed that it is also a more cost-effective buffer zone than traditional fixed width ones.

In Paper II, it was shown that mapping wet areas improved the predictions of redox sensitive elements and elements with high affinity for organic matter. Wet areas, especially when located in riparian soils, are source areas for many water pollutants. Water pollutants can be easily mobilized into streams if the source areas are compromised by forestry practices. Wet riparian soils are also the central sites for many biogeochemical processes in the catchment. Within the riparian zone, the groundwater hotspots serve as a good predictor for locations with higher species diversity. In groundwater hotspots, the higher moisture reduces the bearing capacity of the soils (Block *et al.*, 2002; McNabb *et al.*, 2001) making them more susceptible to rutting and as potential threats of sedimentation to streams. As such, protecting the wet areas and groundwater hotspots in the riparian zone can reduce the risk of water pollution while maintaining biodiversity, thus sustaining the ecological integrity of the buffer zone.

The economic analysis showed that hydrologically adapted buffer zones created using wet areas and groundwater hotspots were more cost effective than traditionally used fixed width options. Both buffer zones had average NPV (3400 USD ha^{-1}) within the same order of magnitude for the productive forest area. However, the hydrologically adapted ones were cheaper per hectare when considering the entire catchment area (productive forest and low-productive forest). This was because there was a larger portion of less productive forests (20%) in the hydrologically adapted buffer zones than in the fixed width buffer zones. Using wet area mapping and groundwater hotspots captured a larger portion of wetlands including riparian wetlands where soils are often waterlogged and trees have lower diameter at breast height (DBH). As such, wet area combined with groundwater hotspots created a variable width buffer zone that is narrower in dry areas where trees that are more productive are found and wider in wet areas with low productive trees.

Findings from other recent studies has also shown that retaining trees in low productive areas are a cost effective strategy for designing riparian buffer zone (LeDoux & Whitman, 2013; Qiu *et al.*, 2009). Not only can hydrologically adapted buffer zones reduce the cost of buffer zones by limiting the number of productive trees in the buffer zones, but also can reduce the cost due to forest traffic ‘surprise’s’. Making groundwater hotspots and wet areas, machine free zones can prevent damages to forest machines as well as soil destruction.

4 Conclusion

In the quest to understand how the boreal catchment functions, this thesis demonstrated that natural variability of stream chemistry are both spatially and temporally dependent on the hydrological connectivity of landscapes to streams. Using this knowledge indicated that both climate change and forestry will impact water quality changes in the future. By understanding the hydrological conditions of the catchment, cost effective riparian zones can be created around wet areas groundwater hotspots to improve the environmental protection. More specifically, by investigating how landscape components interacts and evolve from small spatial scales to larger catchment scales, it was found in Paper I that:

- The role of surficial landscape characteristics changes from being the dominant regulator of stream chemistry in small headwater catchments, to being dominant only during high and intermediate flows in larger catchments.
- Instream processes were not found as an important regulator of stream DOC as the quantity of DOC lost to bacterial degradation and photo-oxidation was small.
- Deep groundwater input is an important component during baseflow which dilutes DOC signals in larger catchments, and increases the concentration of weathering derived elements.

More specifically, classification of the landscape into distinct attributes improved the understanding of the mobility and retention of diverse element into streams. A clear distinction could be seen between the conservative elements and the more complex elements (Paper II):

- Conservative elements which were mainly derived from weathering were not limited by the hydrology or the connectivity of the landscape

- Redox sensitive elements and those with high affinity for organic matter were best predicted by identifying source areas such as riparian soils
- Other elements that derive from atmospheric deposition and DOC were best predicted using the landscape connectivity approach

When these conceptual catchment understandings were applied to advance knowledge on how stream chemistry will change in the future, I found that the outcome largely depended on the scale of the catchment. For instance, in Paper III it was shown that:

- Both climate change and forestry effects will increase DOC concentrations and fluxes in the future.
- On the larger spatial scale, aggregation of small scale effects showed an additive effect under the climate change plus forestry scenarios

Further application of catchment understandings enabled the development of a new method for protecting surface water quality. Based on the hydrological and biogeochemical understandings of the catchment, hydrologically adapted buffer zones were created using site-specific conditions of the riparian zone. Evaluating the monetary cost of this buffer zone I could show that (Paper IV):

- Hydrologically adapted buffer zones were cheaper per hectare than fixed width ones because they target wet areas and groundwater hotspots where low productive forest were found.
- An implication of this is that the protection of surface water quality can be improved, by protecting a larger area that needs the most protection, at no additional cost.

5 Future Perspectives

The way forward in catchment research lies in further utilizing interdisciplinary research to link various aspects of the environment so as to understand the current conditions and be able to adapt to future changes.

For the water resources, the way forward lies in further investigating groundwater and surface water interaction at a range of spatial and temporal scales. This can provide a better understanding of the hydrology in the catchment specifically the role of physical, chemical and biological processes in influencing groundwater and surface water interaction and how these will change in future climate conditions. Another advance would be to show the effects of environmental considerations in forest management such as the use of hydrologically adapted site specific riparian buffer zones on the structure and functions of aquatic and terrestrial ecosystems.

Natural disturbances from wild fires, wind disturbance and insect infestation could likely be exacerbated by future climate change and landuse practices. Future investigation should therefore be focused on investigating how these combined threats can influence water quality so as to better adapt.

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