Groundwater connections between the boreal landscape and its headwater streams: the role of discrete riparian inflow points (DRIPs)

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Abstract

River networks connect the Swedish boreal landscape with the Baltic Sea. Groundwater provides a majority of the river water, and therefore it is important to understand the mechanisms of groundwater-stream interactions. The riparian zone, or near stream area, is an important terrestrial interface where groundwater becomes stream water. This thesis focused on riparian areas where subsurface flow paths converge, referred to as discrete riparian inflow points (DRIPs). DRIPs connect a large part of the landscape with a narrow section of the stream, and therefore represent landscape connectivity between hillslope and catchment scales. Results showed that DRIPs have near-surface groundwater levels and organic-rich groundwater chemistry. Combined with flow path convergence, this facilitates high mobilization rates of organic-rich groundwater to local points along stream reaches, which affects local stream ecosystems as well as downstream transport of carbon. Moreover, the response of DRIPs to changing hydrological conditions indicated that hydrological processes deviate from the rest of the riparian zone. Interactions between groundwater, peat-rich soil, vegetation and biota can be attributed to the contrasting characteristics of DRIPs compared to the rest of the riparian zone. This thesis demonstrated that DRIPs play an important role in both terrestrial and aquatic ecosystems in the Swedish boreal landscape. Therefore, DRIPs need to be explicitly considered in sustainable forest management.

Keywords: DRIP, boreal, landscape, connectivity, stream, riparian, groundwater, forest, hydrology, carbon

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Grondwater verbindingen tussen het boreale landschap en eerste orde beken: de rol van discrete riparian inflow points (DRIPs)

Abstract

Rivier- en beeksystemen verbinden het Zweedse boreale landschap met de Baltische zee. De beken worden voor een groot deel gevoed door grondwater, en daarom is het belangrijk om de interacties tussen grondwater en beeksystemen te begrijpen. De oeverzone speelt daarbij een belangrijke rol voor de water kwaliteit: dit zijn de laatste meters bodem waar het grondwater mee in aanraking komt, voordat het uittreedt naar oppervlaktewater. Het onderwerp van deze thesis is de convergentie van ondergrondse stroombanen in oeverzones, zogeheten discrete riparian inflow points (DRIPs). DRIPs verbinden een groot deel van het landschap met een smal deel van de beek, en daarom beslaan DRIPs een ruimtelijke schaal die tussen hellingen en stroomgebieden valt. De resultaten laten zien dat in DRIPs het grondwaterpeil aan het oppervlak ligt, en het grondwater rijk is aan opgelost organische stof. In combinatie met de convergente stroombanen, zorgt dit voor de mobilizatie van grote hoeveelheden koolstofrijk grondwater naar specifieke locaties in de beeksystemen. Dit beïnvloedt de lokale ecosystemen in de beek, maar ook het transport van koolstof via open water. Verder blijkt dat de neerslagrespons van DRIPs andere hydrologische processen teweeg brengt, ten opzichten van omringende oeverzones. Interacties tussen grondwater, veen-rijke bodem, vegetatie en organismen zijn belangrijk voor het verklaren van de karakteristieken van DRIPs. De resultaten van deze thesis laten zien dat DRIPs een belangrijke rol spelen voor oevers en beeksystemen in het Zweedse landschap. Daarom moeten DRIPs expliciet worden meegewogen in duurzaam bosbeheer.

Keywords: DRIP, boreaal, landschap, grondwater, beken, oever, bos, hydrologie, koolstof

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I. Ploum, Stefan W, Leach, Jason A, Kuglerová, Lenka and Laudon, Hjalmar (2018). Thermal detection of discrete riparian inflow points (DRIPs) during contrasting hydrological events. Hydrological Processes, 32 (19), 3049-3050.

II. Ploum, Stefan W, Laudon, Hjalmar, Peralta-Tapia, Andrés and Kuglerová, Lenka (2020). Are dissolved organic carbon concentrations in riparian groundwater linked to hydrological pathways in the boreal forest? Hydrology and Earth System Sciences, 24 (4), 1709-1720.

III. Ploum, Stefan W, Leach, Jason A, Laudon, Hjalmar and Kuglerová, Lenka. The role of discrete riparian inflow points (DRIPs) in boreal landscape-stream connectivity (submitted)

IV. Ploum, Stefan W, Lupon, Anna, Leach, Jason A, Kuglerová, Lenka and Laudon, Hjalmar. Shift in controls of longitudinal DOC patterns along a boreal headwater stream (manuscript)

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The contribution of Stefan W Ploum (SWP) to the papers included in this thesis was as follows:

I. SWP was the main person responsible for data collection and analysis, video editing, narration, writing and submission

II. SWP was the main person responsible for data collection and analysis, writing and submission

III. SWP was the main person responsible for the concept, data collection and analysis, writing and submission

IV. SWP was the main person responsible for data collection and analysis, model development, and writing

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Abbreviations

DOC	Dissolved organic carbon
DRIP	Discrete riparian inflow point
DTS	Distributed temperature sensing
EC	Electrical conductivity
FO	Fiber optic
LMM	Linear mixed-effects model
OM	Organic matter
RZ	Riparian zone
TWI	Topographic wetness index
UCA	Upslope contributing area
VSA	Variable source area

1. Introduction

"One cannot step in the same stream twice" is what Heraclitus allegedly stated around 500 BC. Still today, catchment scientists aim to understand why that is the case. In that regard I like to add that one cannot sample the same groundwater twice, because the changes that we observe in rivers and streams are often the result of what happens belowground in the surrounding landscape. Groundwater travels through soils and bedrock to streams, rivers and lakes. Along its journey, water changes in temperature and chemical composition. Groundwater flow paths largely determine how streams and rivers respond to "hydrological triggers", such as rain or snowmelt episodes. Soil and bedrock properties, land cover type, and topography affect flow path distributions, which determine where and when groundwater becomes stream water. As such, belowground processes propagate to the surface, driving phenomena we can visually observe, for example droughts or floods. Interactions between groundwater and streams are thus essential in many questions with regard to water, such as preservation of ecosystem services and water resources, mitigation of climate change, and understanding anthropogenic impacts on natural systems. This thesis contributes to the understanding of how above- and belowground flow paths interact with each other, and the ecosystems they flow through. Specifically, the objective of this thesis is to fill knowledge gaps regarding groundwater-stream interactions in the boreal landscape.

1.1 Landscapes as catchments

In order to understand interactions between groundwater and surface water, we often categorize landscapes in different sub-units. For example, lakes, rivers and mires are easy to distinguish from each other. However, streams can be a little harder to find, especially the smallest ones (Bishop et al., 2008). Topographic maps can help with finding streams by delineating catchments, which are areas that theoretically drain to the same point. If a catchment is large enough, the capacity of the soil to carry water belowground can be exceeded (Dunne et al., 1975; Hewlett and Hibbert, 1967). Water will start to run over the surface, and a stream channel will begin to take shape. Climate (e.g. rainfall intensities and amounts), the shape and slope of valleys, bed material, and vegetation affects the size and shape of streams. These conditions vary among landscapes, and therefore stream networks are often complex. In the Swedish boreal system, it requires approximately 10 ha, or 100 000 m^2, of catchment area to initiate a stream channel that can sustain (almost) continuous streamflow throughout most years (Ågren et al., 2014). This also means that if you take a water sample at the head of a stream, the chemical composition of that water sample is the net result of soil-groundwater interactions occurring in an area as large as twenty football fields. However, most of the time a large part of that area does not actively contribute water to the stream because groundwater flow paths are not connected. Therefore, in order to understand the dynamics and composition of stream water, it is important to elucidate how groundwater flow paths are organized in the landscape.

1.2 Landscape connectivity

From hillslopes to streams, subsurface flow paths become increasingly more connected. With increasing drainage area, variable source areas (VSA) (Beven and Kirkby, 1979) and zero-order basins (Tsukamoto and Ohta, 1988) can be identified in the landscape. These convergence zones of groundwater presumably have a large control on streamflow generation. Topography can be useful to predict areas where subsurface flow paths converge. For example, topographic wetness index (TWI) is commonly used to spatially identify wet areas, or areas with groundwater levels near the surface (Beven and Kirkby, 1979). However, topography based tools do not account for complex subsurface geology (Devito et al., 2005), and might not be representative in areas with small topographic gradients. Moreover, it has been pointed out that most of the time VSA's are not hydrologically active, and while their response to rainfall might be quicker than "non-VSA" areas, this highly depends on antecedent conditions (Ambroise, 2004; Klaus and

Jackson, 2018). As such, topography can be useful for exploring flow path convergence in landscapes (O'Callaghan and Mark, 1984), but does not directly represent the spatiotemporal variability in runoff generation. Moreover, this landscape connectivity approach originates from a hydrological point of view, and does not account for chemical, or biological processes that can be associated with flow path convergence. For example, soil chemistry regimes change with wetness conditions (Vidon, 2017), and groundwater regimes affect distributions of plant species (Jansson et al., 2007; Kuglerová et al., 2014a). In the riparian zone (RZ), the area directly surrounding streams, these various aspects come together, and the landscape connects with the stream (Buttle, 2002).

1.3 Boreal riparian zones

Swedish boreal RZ's are typically characterized by peat soils (Seibert et al., 2007). Cold and wet soil conditions promote the build-up of organic matter (OM), outpacing microbial decomposition rates. Because the underlying mineral soil often is less conductive compared to the peat-rich top soil, catchment water that reaches the RZ mostly routes through the OM (Bishop et al., 2011; Seibert et al., 2009). The routing of water through the organic top soil facilitates the transport of OM to streams as dissolved organic carbon (DOC) (Bishop et al., 1990). However, the RZ is spatially and temporally heterogeneous. Boreal RZ's are diverse in vegetation (Kuglerová et al., 2014a), can experience periodic flooding, and are subjected to fluvial processes (Polvi et al., 2014). Also belowground, the RZ is diverse. Studies on spatial heterogeneities in the RZ demonstrated that peat layer thickness and groundwater table regimes can be considered major explanatory factors for spatial differences in groundwater chemistry (Grabs et al., 2012; Ledesma et al., 2018a; Lyon et al., 2011). This narrow but complex strip of land plays an important role in the transport of DOC to streams.

1.4 Stream chemistry

DOC gives boreal streams their characteristic brown color, which originates primarily from the RZ (Ledesma et al., 2018a). Once DOC is transported from riparian peat soils to the stream, it is exposed to a different environment: sunlight, flowing water, exposure to the atmosphere, and hungry aquatic microbes (Casas-Ruiz et al., 2017). Some of the DOC will be directly incorporated in local carbon cycles, and some will be transported downstream, where its fate is determined by the conditions it encounters there (Raymond et al., 2016). While this is only a small part of the carbon cycle, this variability in the fate of riparian DOC plays an important role in boreal stream ecosystems. This is especially the case for the headwaters, as lateral inputs of shallow groundwater exert a large control on stream biogeochemistry (Peralta-Tapia et al., 2015). Furthermore, particular stream sections which have a large influence on stream chemistry can be identified as biogeochemical hotspots or control points (Bernhardt et al., 2017; McClain et al., 2003). Focusing on the processes that occur in these parts of the stream network can potentially explain a large part of the total variability in stream chemistry. This means we have to combine physical and biological processes in both terrestrial and aquatic systems to understand why stream chemistry continuously changes.

1.5 Research objectives

In this thesis, the goal is to understand how groundwater connects the boreal landscape with small streams. Based on previous work, I focused on riparian areas where flow paths converge. I refer to these as discrete riparian inflow points, or DRIPs. Because DRIPs connect large parts of the catchment with a narrow section of the stream, it is likely that their control on stream chemistry and streamflow is relatively large compared to the rest of the RZ. The objective of this thesis is to understand the role of DRIPs in connecting landscapes and streams, from hydrological and biogeochemical viewpoints. The specific objectives are:

- The objective of paper I was to detect whether DRIPs have hydrological influence on a stream.
- The objective of paper II was to characterize the groundwater chemistry of DRIPs.
- The objective of paper III was to describe how DRIPs compare to the rest of the riparian zone in their hydrology, biogeochemistry and vegetation
- The objective of paper IV was to understand the influence of DRIPs on stream chemistry

2. Methods

2.1 Krycklan catchment

The studies in this thesis were conducted in headwaters of the Krycklan study catchment (64°14´N, 19°46´E), which is located approximately 50 km northwest from Umeå, Sweden (Fig.1A-B). The study area is part of the Svartberget research forest. The Krycklan catchment area is 67.90 km^2, is dominated by forest cover (87 %), but also includes mires (9%) and lakes (1%) (Laudon et al., 2013). The climate is a cold temperate humid type, with snow cover for approximately 5 months per year. Between 1981 and 2010, the mean annual precipitation was 614 mm, of which approximately half falls as snow (Laudon et al., 2013). Mean annual runoff was 311 mm, remaining on average 303 mm of evapotranspiration. Mean air temperature was 1.8 °C, with January as the average coldest month (-9.5 °C) and July the warmest on average (14.7 °C). Discharge regimes are snowmelt dominated, and characterized by winter low flows until spring (May) followed by snowmelt induced peak flows up to June. From June to September, low flow conditions are alternated by rain induced hydrological events. In the autumn, rain and rain-on-snow events can produce peak flows until approximately December, when temperatures stay consistently below 0 °C and streamflow reduces to baseflow conditions.

2.1.1 Geological setting

In the Krycklan catchment, bedrock consists mostly of Svecofennian metasediments or metagraywacke (94%). Quaternary deposits consist predominantly of till soils (50%) in the higher elevated areas, up to 405 meter above sea level (m a.s.l.), and sorted sediments (30%) in lower parts of the catchment (down to 114 m a.s.l.) (Laudon et al., 2013). Positioned at the highest coastline (approximately 257 m a.s.l.), there is a sharp delineation in the catchment between post-glacial, till soils, and sedimentary and fluvial deposits (Lindén et al., 2006). In the headwaters, mineral subsurface fractions consist of glacial deposits of various depths (0-30 meters), different degrees of consolidation, and grain sizes varying from boulders to silt (Ivarsson and Johnsson, 1988; Lindqvist et al., 1989). The headwater channels generally slope in northwest-southeast direction, which is similar to the dominant direction of ice movement during the last glaciation. Basal tills were deposited below the glacier and therefore became highly compressed and almost impermeable. Basal till compositions are finer at lower elevations, and coarser at higher elevated parts of the area, where also gneissic bedrock is exposed. At the lee side of the glacier, deposits of ablation till (material carried on top of the ice) were found which filled up depressions in the landscape (Ivarsson and Johnsson, 1988). Compared to the basal till, these deposits were less compressed, and predominantly sandy, but characterized by its heterogeneity in grain size, including large boulders. Advancing of the ice sheet may have compressed some of the ablation till. Ivarsson (2007) demonstrated that in a nearby study area (~50 km, Lycksele), local topography was important for spatial dynamics in glacial till deposition. He pointed out that hills were prone to frost conditions until a late stage of deglaciation, stabilizing fine-grained materials on elevated landscape positions. Also, glaciofluvial processes and geological weaknesses in the bedrock were documented as explanatory factors for spatial differences in grain sizes of glacial deposits. Furthermore, Ivarsson (2007) reported that the degree of compaction was highly variable in the upper 2 meters, but that compact till was dominating.

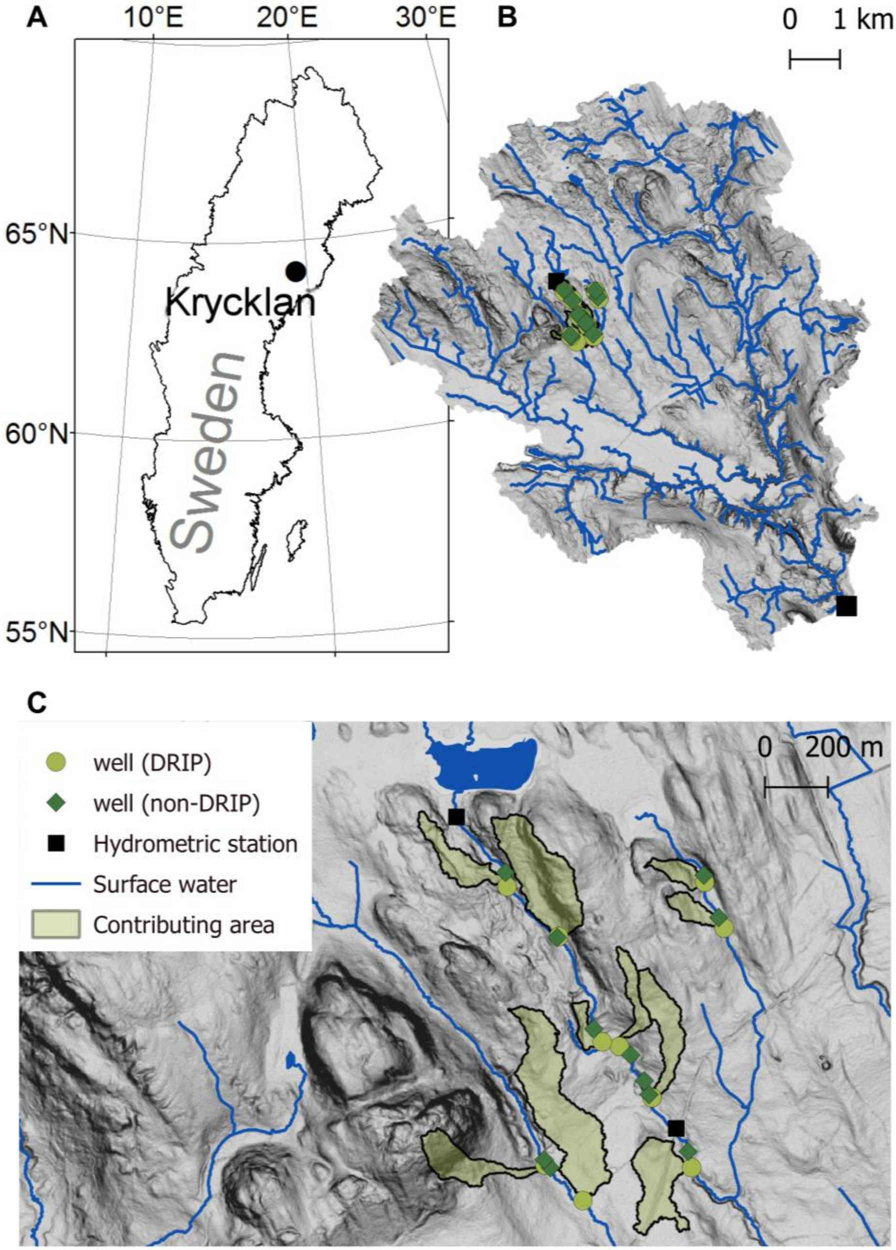

Figure 1 Study area overview. Panel A shows the location of the Krycklan catchment in Sweden. Panel B shows the perennial stream network of the Krycklan catchment in blue, and the study area (green symbols). Panel C shows the study area, with well transects locations, and their contributing area (green areas). Panel A is adapted from paper III, panel B and C are adapted from paper II.

2.2 Groundwater observations (paper II, III, IV)

2.2.1 Well network

The site selection for the groundwater well network was based on TWI and flow accumulation algorithms (Ågren et al., 2014; Beven and Kirkby, 1979; O'Callaghan and Mark, 1984). In the field, DRIPs were visually confirmed as wet corridors, dominated by moss cover, wet soil conditions with poor load bearing capacity, and a decrease in tree density compared to adjacent RZ. The selected DRIP sites had a mean UCA of 270 000 m^2 and adjacent non-DRIP sites a mean UCA of 18 m^2 (Fig. 1C). The well network consisted of 69 fully screened PVC wells (30 mm diameter), of which 60 in a paired transect setup, and 9 additional wells. The paired transects consisted of riparian wells (95 cm mean depth) in the direct vicinity of the stream (1-5 meters), a transition well (99 cm mean depth) at 10 meters from the stream, and an upland well (121 cm mean depth) approximately 20 meters from the stream. The wells were installed following the local topography and vegetation patterns to approximate the local hydraulic gradients and flow paths. The fully screened wells represented a weighted average of the phreatic aquifer, which has been documented to have a non-linear hydraulic profile towards the surface (Bishop et al., 1990). Furthermore, groundwater levels of six wells were monitored in 2018. Water level time-series were obtained using TruTracks WT-HR 64K, with an aggregated hourly time step. The loggers were installed in wells directly next to the riparian sampling wells. The water height was converted to groundwater level relative to the surface, using the well depth and casing height. At data collection moments, manual measurements were collected to correct time-series.

2.2.2 Groundwater sampling

The well network was sampled using suction cup lysimeters and vacuumed glass bottles (Blackburn et al., 2017). The wells were pumped before installing the suction cups to ensure that water from the aquifer was sampled without any stagnant well water. The bottles were collected after approximately 24 hours and subsampled, filtered and analyzed within 48 hours. In addition, a more intensive sampling campaign was conducted for a series of riparian wells only. These were sampled following a similar protocol, but instead of suction cup lysimeters, a peristaltic pump was used for the collection of water samples. For paper II, groundwater samples were collected during spring, summer and autumn of the hydrological years 2016 and 2017. In total 359 samples were analyzed from six sampling campaigns, of which 200 from DRIP wells and 159 from non-DRIP wells. Non-DRIP wells occasionally had too low water level to collect a representative water sample. For paper IV, 190 riparian groundwater samples were used, partially from additional sampling campaigns in the spring 2018 and 2019. For analysis of dissolved organic carbon (DOC), a subsample was filtered (0.45 μm) into acid-washed high-density polyethylene bottles (rinsed three times) and kept at 4 °C before laboratory analysis. DOC was measured by acidifying the sample and combustion using a Shimadzu TOC-V_{CPH}. The pH and EC samples were subsampled without headspace into acid-washed high-density polyethylene bottles (rinsed three times) and kept at 4 °C before laboratory analysis. Samples were analyzed using a Mettler Toledo DGi117-Water probe for pH and Mettler Toledo InLab741 probe for electrical conductivity.

2.3 Stream observations (paper I, III, IV)

2.3.1 Stream reach

The stream Stortjärnbäcken is the main study reach in papers I and IV (Fig. 2). The stream originates from a headwater lake. The C5 hydrometric station is located about 100 meters downstream of the lake. The stream flows for 1.5 km through a forest before reaching hydrometric station C6. The hydrological regime at both hydrometric stations is dominated by the annual snowmelt peak, occurring around May (100-200 l/s). In the summer and autumn, low flows dominate (5-10 l/s) but are alternated with medium to high flows (25-75 l/s) as a response to rain events. During the winter and early spring, the stream is snow and ice covered with flows around 1-2 l/s. At C5, streamflow is mostly driven by lake level variations, which dampens and delays peak flow events compared to the C6 streamflow record. At C6, hydrographs are characterized by steep rising limbs, but lake water from C5 remains a dominant component of the discharge and chemistry at C6 (Leach and Laudon, 2019). The lateral inputs from the riparian zone between C5 and C6 are for a large part routed through DRIPs. DRIPs connect 60% of the C5-C6 catchment area to 5% of the stream length (Leach et al., 2017). The remaining 40% of the catchment area is reaching the stream channel through non-DRIP riparian areas. The stream reach is marked by a series of sampling locations, dividing the reach in 28 sections of approximately 50 meter (Lupon et al., 2019). At each sampling location, grab samples were taken simultaneously with the groundwater sampling. The lab analysis followed the same protocol as the groundwater samples.

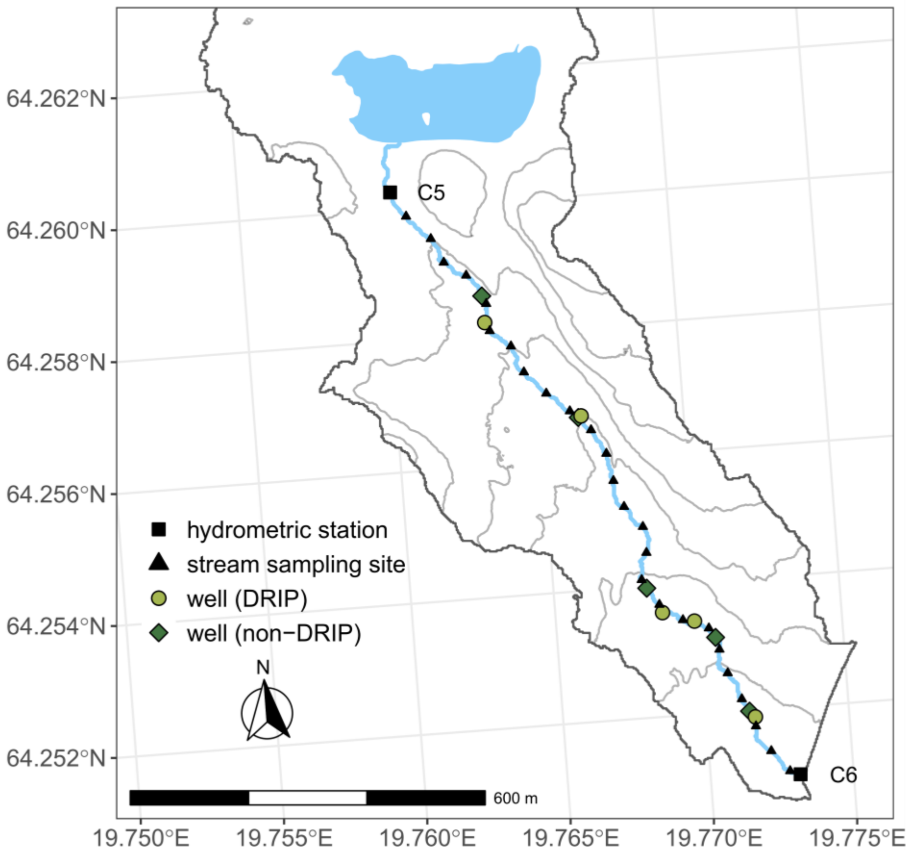

Figure 2 The C5-C6 stream reach. In black, squares indicate the hydrometric stations. and triangles show the stream sampling sites. DRIPs and non-DRIPs wells are indicated with light green circles and dark green diamonds, respectively. Figure adapted from paper IV.

2.3.2 Distributed temperature sensing

The stream temperature sensing infrastructure was setup by Leach et al. (2017). The C5-C6 reach was equipped with a total of 1700 m fiber optic cable. The cable connected to a Silixa XT-DTS, which provided a stream temperature profile with a sampling resolution of 0.25 m and 0.01 °C temperature resolution. The distributed temperature sensing (DTS) technique is based on travel time of light through the fiber optic cable (Selker et al., 2006). The cable conditions at different distances from the source can be derived from the difference between the emitted signal and the received signal. Cable temperature can be derived from repeated series of samplings, which were calibrated using ice baths and two PT100 thermistors (accuracy 0.1 °C). The DTS unit intermittently logged temperature between the September 2015 and May 2018.

2.3.3 Scaling DOC concentrations

For comparison of DRIPs, non-DRIPs and stream DOC concentrations across the Krycklan catchment, a set of streams (C1, C2, C7, C9, C12, C13, C15, C16) is selected from the stream monitoring program between 2017 and 2019 (Laudon et al., 2013). The selected streams are forest dominated, have till dominated soils and have catchment sizes that range from 12 ha to 67.9 km^2. In addition, average DOC concentrations from hillslope transects are presented from Grabs et al. (2012), which cover upslope contributing areas up to 1200 m^2, bridging the range between non-DRIPs and DRIPs. The groundwater and stream DOC concentrations are divided in three periods: drought conditions, rain-dominated conditions and snowmelt conditions. The drought conditions originate from a lake damming experiment in 2017 and the summer of 2018, which was one of the most severe drought years in Sweden (Gómez-Gener et al., 2020).

2.4 Stream DOC model framework (paper IV)

In paper IV, riparian groundwater samples are used in a model framework to predict stream DOC concentrations. The simulations were compared to the observed stream DOC concentrations at the stream sampling locations (i). The framework considered the stream DOC concentration ($DOC_{stream,\, i}$) to be the result of upstream water ($DOC_{stream,\, i-1}$) mixing with the net gained lateral riparian groundwater flux (DOC_{rip}). Riparian DOC inputs were subjected to in-stream uptake ($uptake_{rip,\, i}$).

$$DOC_{stream,i} = \frac{\left(DOC_{stream,i-1} Q_{i-1}\right) + DOC_{rip,i}(Q_i - Q_{i-1}) - uptake_{rip,i}}{Q_i}$$

where Q_i and Q_{i-1} are the stream discharge at locations i and i-1, respectively. This equation was used in combination with different assumptions for the terms that represent the gain of streamflow by riparian groundwater inputs and biological uptake. This resulted in four different models with the following assumptions:

- Model DIFF_NOBIO assumed that net gained streamflow is the result of diffuse groundwater contributions that are evenly distributed along the reach. There is no biological uptake of DOC.
- Model DIFF_BIO assumed that net gained streamflow is the result of diffuse groundwater contributions that are evenly distributed along the reach. There is biological uptake of DOC downstream of DRIPs until the next sampling point.
- Model UCA_NOBIO assumed that net gained streamflow is the result of distributed groundwater contributions that are distributed along the reach relative to the upslope contributing area of each stream section. There is no biological uptake of DOC.
- Model UCA_BIO assumed that net gained streamflow is the result of distributed groundwater contributions that are distributed along the reach relative to the upslope contributing area of each stream section. There is biological uptake of DOC downstream of DRIPs until the next sampling point.

2.4.1 Riparian DOC concentrations

In addition to the model results in paper IV, I present an exercise that reduces the available riparian DOC information. I consider four levels for representing riparian DOC inputs (Fig. 3). The model in Paper IV is based on the fourth level, which means all the available riparian DOC concentrations are used as data input. On the first level, riparian DOC concentrations were uniform along the reach: all lateral inputs were based on the averaged DOC concentrations (level 1) during each sampling. On the second level riparian DOC concentrations area were averaged as well, but the mean for DRIP, and non-DRIP riparian zones were calculated separately (level 2). On the third level, DOC concentrations of non-DRIP locations were averaged, but individual groundwater DOC concentrations were used for the stream sections with a DRIP (level 3). Finally, on the fourth level all groundwater wells were used individually.

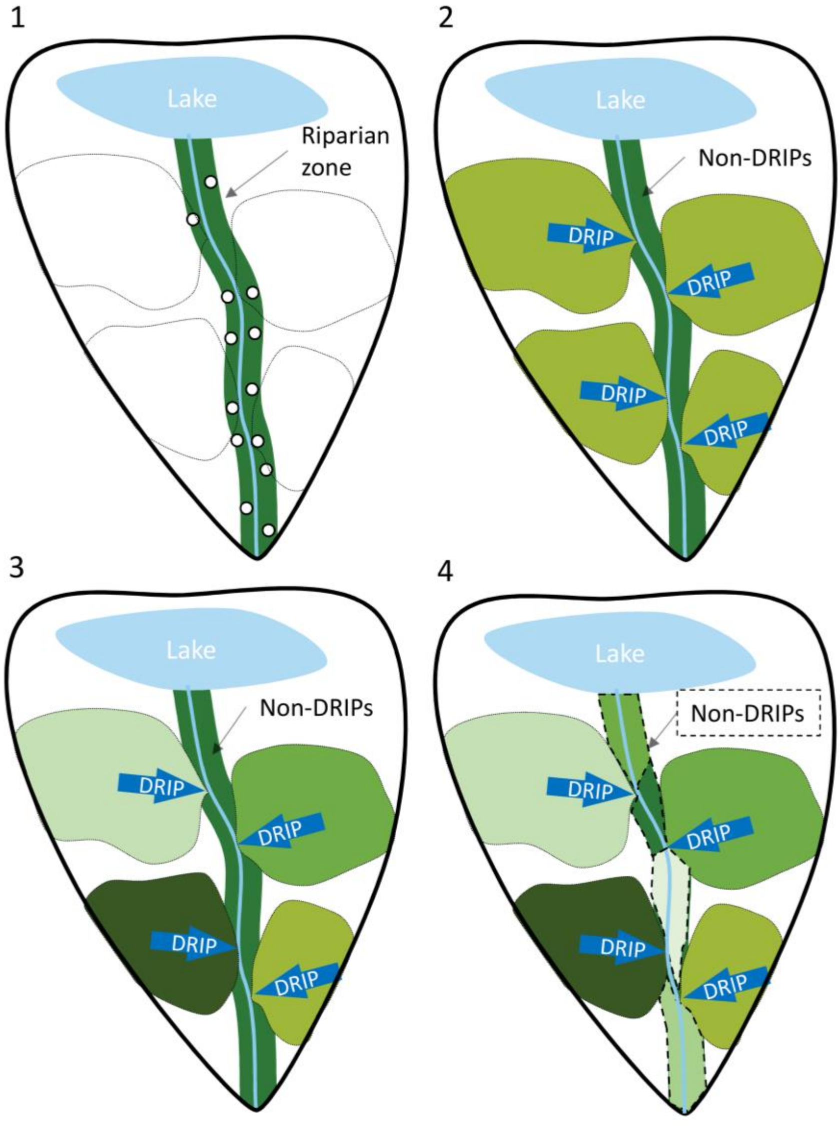

Figure 3 Representation of riparian DOC concentrations. Panel numbers correspond to the different levels of representation. The different shades of green suggest differences in DOC concentrations.

3. Results and discussion

3.1 Assessing the hydrological role of DRIPs

Interactions between groundwater and streams can be considered a multi-directional process. Besides the lateral interaction with riparian groundwater, there is the vertical exchange of the open-water channel and the streambed, and longitudinal hyporheic exchanges with stream banks and other channel features (Zimmer and McGlynn, 2018). When the dominant direction of these interactions is towards the open channel, a stream reach gains water. When more water leaves the channel than there is coming in, it can be considered a losing reach. To assess the hydrological role of DRIPs along stream reaches, it is important to consider the different groundwater-stream interactions that control longitudinal changes in streamflow. The DRIP concept focusses on lateral riparian groundwater contributions, assuming gaining flow conditions.

3.1.1 Detection of DRIPs (paper I)

The initial detection of DRIPs, or previously referred to as groundwater discharge zones, was based on distinct vegetation communities, and increased soil wetness conditions compared to the surrounding RZ (Fig. 4C) (Jansson et al., 2007; Kuglerová et al., 2014a). Topography-based prediction of soil wetness allowed to explore the locations of DRIPs at a broader scale than field-based observations (Ågren et al., 2014, 2015). At the main study area, the C5-C6 reach, stream temperature profiles (Fig. 4A) and stable water isotopes were used to evaluate the topography-based predictions (Leach et al., 2017). This evaluation demonstrated that the location of DRIPs can be predicted with topography, but quantification of streamflow contribution requires additional information. While step changes in the stream temperature profiles coincided with the location of DRIPs along the stream reach, their detectability relied on thermal gradients between the groundwater and stream reach. Paper I demonstrated that throughout different seasons and flow conditions this detectability is highly variable (Ploum et al., 2018). Several factors contributed to this change in detectability of DRIPs along the stream reach.

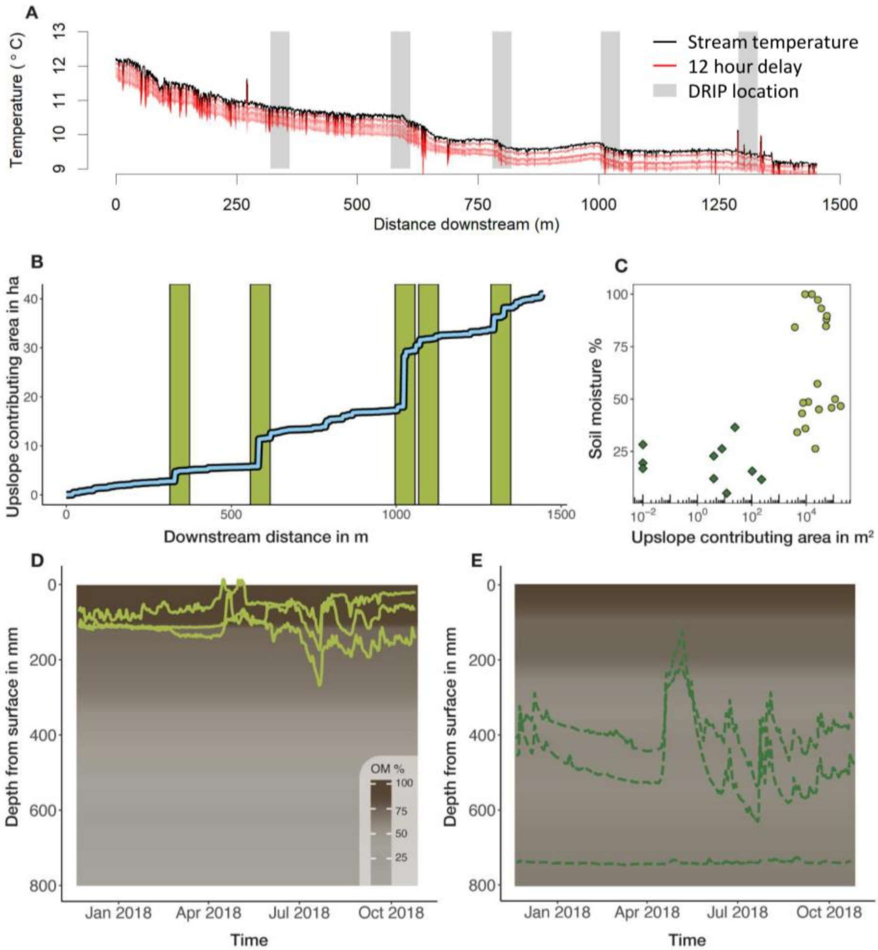

Figure 4 Overview of hydrological assessment of DRIPs. Panel A shows an example of a stream temperature profile from the DTS, with DRIPs indicated by grey bars. Panel B shows the change in UCA along the reach in blue and DRIPs in light green. In panel C soil moisture percentages are plotted against UCA, with DRIPs in light green circles and non-DRIPs in dark green diamonds. Panel D and E show groundwater levels of three

DRIPs (light green) and three non-DRIPs (dark green) in 2018, respectively. The background color represents the OM percentage of the soils. Panel A is adapted from paper I, panels B-E are adapted from paper III.

First, the net gain in streamflow along the reach changes during events. Paper IV showed that the gain in streamflow ranged from 8% to 90%, and was on average 37%. During the rising limb of a hydrograph, RZ contributions quickly increased as a response to rainfall or snowmelt. The upstream lake was slower in response than the riparian groundwater, and therefore the lake contributed most stream water during peak flows and receding limbs. As such, the stream temperature at the start of the reach relied on the lake conditions, which can affect the detectability of the lateral inputs of riparian groundwater along the reach. Secondly, the temperature of the riparian groundwater was variable between seasons. In spring, snowmelt water was observed to run over the surface and over ice sheets, which cooled down water to near freezing temperatures. While both lateral inputs, and the stream water were both in the range of 0 °C to 3 °C, we observed during a rain-on-snow event that the relative warm lake and rain water contrasted with the cold meltwater that was contributed by DRIPs. Thirdly, changes in stream temperature at the DRIPs suggested that each DRIP responded differently to hydrological conditions. While at some DRIPs stream temperatures rapidly declined at the onset of an event, at other DRIPS stream temperatures were slower to respond but remained at a stable temperature. This suggests that DRIPs can have specific responses to changing hydrological conditions. However, to quantify the different hydrological inputs from DRIPs and non-DRIPs, it requires multi-method approaches, including for example hydraulic gradients, tracer injections or mixing models.

3.1.2 Groundwater regime

Paper III demonstrated that groundwater levels at DRIPs were consistently near the surface (Fig. 4D). This is in contrast to non-DRIP riparian areas with groundwater levels approximately 50 cm below the surface, which increased in response to rainfall or snowmelt (Fig. 4E). Time-series of groundwater levels can indicate when lateral water fluxes change. However, it is important to note that in boreal till soils the lateral hydraulic conductivity commonly increases towards the surface (Bishop et al., 1990; Rodhe, 1989). This means that lateral water fluxes increase non-linearly when groundwater levels rise towards the surface. The different groundwater levels of DRIP and non-

DRIPs suggests that most of the time, rates of lateral water movement in DRIPs are higher than the rest of the RZ. These contrasting groundwater regimes are important for assessing spatial variability of lateral groundwater contributions to streams during different flow conditions. The combination of thermal techniques and groundwater level monitoring allowed to identify DRIPs as riparian areas that have contrasting streamflow generating processes, compared to the rest of the RZ. This knowledge can improve the design of monitoring infrastructure (Burt, 2005), optimize numerical catchment models (Barclay et al., 2020), and improve hydrology-based management of riparian zones (Buttle, 2002; Kuglerová et al., 2014b; Tiwari et al., 2016).

3.2 Characterizing groundwater chemistry (paper II)

Lateral groundwater contributions are important for stream chemistry, because they introduce water with different properties than the stream. The stream is not just a passive pipe, rather it is responsible for biogeochemical transformation and cycling of carbon, nutrients and other solutes (Cole et al., 2007). The spatial variability in groundwater contributions affects chemical and biological processes in the stream (McClain et al., 2003). For that matter, it is important to characterize riparian groundwater along streams. Groundwater chemistry depends on the soil-water interactions that occur while water travels belowground. The riparian zone is the last terrestrial interface that groundwater interacts with before it enters the stream. It is important to note that across the riparian zone, water residence times can vary from months to hours (Allaire et al., 2015; Hester and Fox, 2020). This means that the control of the RZ on riparian groundwater chemistry is coupled with flow path organization. In paper II the groundwater regimes of DRIPs and non-DRIPs are used as explanatory variables for spatiotemporal variability in riparian groundwater chemistry.

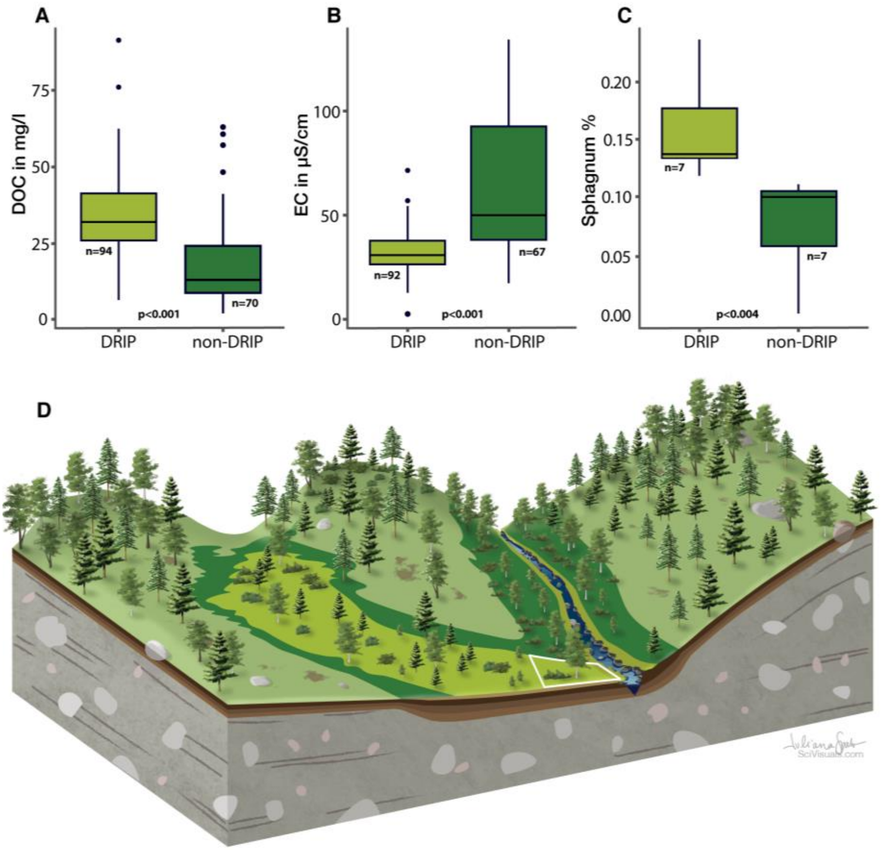

Figure 5 DRIPs and non-DRIPs in the riparian zone. Panel A, B and C show boxplots of DOC concentrations, EC and abundance of *Sphagnum* as a percentage of bryophyte species. Light green colors represent DRIPs and dark green colors represent non-DRIPs. Panel D is an illustration of the riparian zone along a headwater reach, with a DRIP (white box) and its upslope contributing area. Figure is adapted from paper III.

3.2.1 Variability in DOC, pH and EC in groundwater

In the paired well network, DRIPs had significantly different DOC and EC concentrations than non-DRIPs (Fig. 5 A-B). On average, DRIP wells had 1.7 times higher DOC concentrations than non-DRIPs (34 mg/l and 20 mg/l, respectively). In the transects of DRIP wells, DOC concentrations increased 1.24 times over approximately 20 meters lateral distance (from 29 mg/l in the upland wells to 36 mg/l in the riparian wells). In non-DRIPs, concentrations increased proportionally, from 16 to 20 mg/l. The groundwater pH was similar among the groups: mean pH was 5.38 at DRIPs and 5.66 at non-DRIPs. Mean EC in DRIPs (36 µS/cm) was 0.69 times the EC in non DRIPs (52 µS/cm). In the upland wells, both DRIP and non-DRIP wells EC was approximately 40 µS/cm. In DRIPs, the mean EC decreased minimally, to 32 µS/cm in riparian wells, while in the non-DRIP riparian wells mean EC was 1.55 times higher than the upland wells (62 µS/cm). Furthermore, at non-DRIPs the variability in EC increased from upland to riparian wells, while in DRIPs the variability decreased. In spring, summer and autumn the DRIP and non-DRIP groundwater chemistry varied in different ways. In spring, DOC concentrations of DRIPs decreased by 20% compared to summer and autumn (from 34 mg/l to 28 mg/l), while DOC at non-DRIPs showed on average a non-significant increase from 18 to 22 mg/l. The pH in both DRIPs and non-DRIPs increased from summer to autumn (5.37 to 5.70) and was 5.48 in spring. The EC remained stable in DRIP wells, while at non-DRIPs a significant decrease of 5 µS/cm could be observed between autumn and spring.

3.2.2 Contributing factors

The variability in riparian groundwater within the well network was partially explained by the DRIP and non-DRIP areas. As such, the DRIP and non-DRIP categorization of the RZ, together with well position and seasonality, can be used to characterize riparian groundwater chemistry, and link this to their hydrological regimes. The linear mixed-effects models (LMMs) demonstrated that flow paths (DRIP/non-DRIP), well positions, seasons and random effects (the stream and transect identity) explained 68% of the variance in DOC and 70% of the variance in EC. This means that a large part of the spatiotemporal variability can be explained by the considered variables and the interactions between them. This is useful for identifying, and monitoring riparian sections that play an important role in stream biogeochemistry (Bernhardt et al., 2017; McClain et al., 2003). For more detailed groundwater chemistry characterizations, it can be of interest to consider DOC quality (Kothawala et al., 2015), an expanded range of solutes and elements (Lidman et al., 2017), and the distinction of soil-water interactions in different soil horizons (Ledesma et al., 2018b).

3.3 Landscape connectivity (paper III)

Why are hydrological and chemical regimes of DRIPs and non-DRIPs different? To answer this question it is important to consider the interactions and feedback mechanisms in the landscape. Besides the physical and chemical conditions, the biological component has to be included as well. Vegetation patterns were the initial observations that led to the finding that hydrological and chemical regimes at DRIPs were different from the rest of the RZ. Moreover, the long-term patterns of vegetation also determine the composition of the peat in the RZ. Paper III provides a perspective on how hydrology, chemistry and vegetation interact in the landscape, within the DRIP - non-DRIP comparison.

3.3.1 Connectivity and groundwater chemistry

Previous hillslope studies have shown that the soil-water interactions in the RZ are strongly controlled by groundwater level fluctuations and vertical variability in solute concentrations (Blackburn et al., 2017; Grabs et al., 2012; Ledesma et al., 2018b; Lidman et al., 2017). These findings have greatly improved the understanding of first-order groundwater controls on the chemistry of forest streams. However, hillslope transects provide an insight in a two dimensional system, while streams integrate a three dimensional space. To scale processes from hillslope transects to catchments, it is important to consider changes in the connectivity of riparian zones. Moreover, it is important to consider that certain processes might not scale beyond hillslope scale, and other processes might be introduced when connectivity increases. For example, soil wetness typically increases with connectivity of the RZ, which affects regime shifts from oxic to anoxic soil conditions (Vidon, 2017). Furthermore, the extent of wet areas increases with connectivity, which expands RZ soil properties away from the stream (Buttle, 2002). The large upslope contributing area of DRIPs supports the idea that the connectivity of DRIPs is much greater than surrounding RZ, which promotes the extension of riparian-like conditions further upland (Fig. 5D). Further, paper II showed that upland wells at DRIPs had high DOC concentrations 20 meters away from the stream, which suggest that the typical RZ groundwater chemistry extends beyond the near stream area.

3.3.2 Connectivity, vegetation and runoff generation

The extensive wet areas, and the associated soil water chemistry found in DRIPs can affect vegetation succession. Saturated soils are not the ideal environment for the typical boreal forest floor vegetation, such as dwarf shrubs and feather mosses (Kuglerová et al., 2016). Such conditions are however beneficial for peat mosses, *Sphagnum* in particular (Breemen, 1995). DRIPs have relative high abundance of *Sphagnum* compared to non-DRIPs (Fig. 5C), and spatial assessments show their areal cover extends beyond the near-stream areas (Fig. 6A) (Ågren et al., 2015). The different vegetation patterns in the RZ affects the composition of peat (Fig. 6 B-C). While the lateral movement of water in RZ soils has been mostly related to the vertical rise of groundwater level into the organic-rich top soil, the development of *Sphagnum* peat promotes a different routing of water compared to the typical riparian soil profiles.

Wetland studies on *Sphagnum* peat have shown that the living moss layer is highly conductive, while the underlying peat layer has relatively low conductive properties (Breemen, 1995; Nijp et al., 2017). This promotes near-surface, lateral water movement of event water, instead of vertical water movement from below. While in wetland systems it can be assumed that the near-surface lateral flow is dispersed, it is important to note that in DRIPs the dominant hydraulic gradient is likely towards the stream. This suggests that DRIPs route water from surrounding hillslopes, and meteoric inputs directly to the stream, mainly interacting with the living moss layer, instead of the soil underneath. The response of the stable water isotope signature of DRIPs to rain (Leach et al., 2017), suggests that quick routing of event water is likely to occur in DRIPs. Further, the thermal stream profiles suggest that DRIPs can respond quickly to hydrological events as well, despite their relatively large upslope contributing area compared to non-DRIPs (Ploum et al., 2018). The difference in lateral flow rates might be less visible in groundwater level fluctuations, because of the highly non-linear relationship between groundwater level and lateral water movement. While it is not possible to rule out other mechanisms that contribute to these observations, it is an interesting future direction to explore the role of *Sphagnum* peat in the generation of runoff in DRIPs.

Figure 6 Organic top soils of DRIPs. Panel A shows a DRIP covered by *Sphagnum* moss, with the stream at the red bar. Panel B shows the top soil of a DRIP. Panel C shows the top soil of a non-DRIP. Photographs by SW Ploum.

3.4 Scaling of DRIPs across a stream network

The DRIPs studied in this thesis had riparian areas with upslope contributing areas (UCAs) between 7 000 m^2 and 100 000 m^2. In the Krycklan catchment, previous studies have focused on hillslope transects with UCA up to 1 200 m^2, or monitored streams that have catchment areas starting from 120 000 m^2 (Grabs et al., 2012; Laudon et al., 2013). As such, DRIPs fill a gap in the topography-based categories that are commonly used to spatially represent water movement in the boreal landscape (Fig. 7). The explicit consideration of DRIPs in landscape-stream connectivity frameworks, alongside hillslope transects and (fractal) stream networks, can improve the representation of spatiotemporal heterogeneity in groundwater-stream interactions. To characterize groundwater-stream interactions across stream networks during different flow conditions, it can be useful to include DRIPs in the design of water monitoring programs. However, during various conditions there are different processes that need to be considered to capture spatiotemporal variability on network scale. Here I describe the role of hillslopes, DRIPs and streams in the variability in DOC concentrations across the stream network.

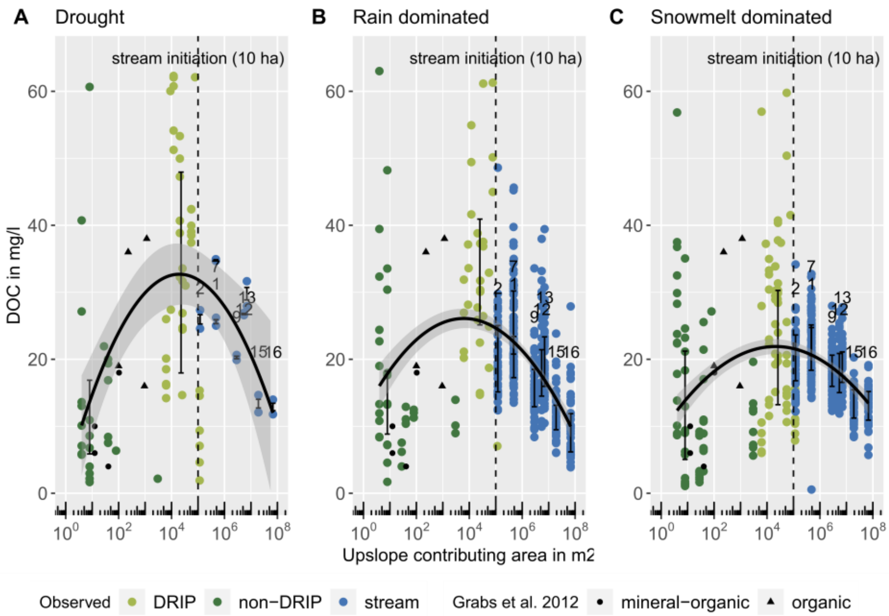

Figure 7 DOC concentrations plotted against upslope contributing area. DRIP groundwater in light green, non-DRIP groundwater in dark green, and stream water in blue. In black the average DOC concentrations from Grabs et al. (2012) are indicated, with distinction between groundwater from mineral-organic (dots) and organic (triangles) riparian areas. Panel A shows a subset of DOC concentrations under (artificial) drought conditions. Panel B shows a subset of rain-dominated conditions and Panel C shows snowmelt-dominated conditions. The solid black line and confidence band shows a fitted line of DOC as a function of UCA. The black error bars show the 25th and 75th percentile of the DOC concentrations in DRIPs, non-DRIPs and streams. The vertical, dashed line indicates the stream initiation threshold in the study area.

3.4.1 Drought

During (artificial) drought conditions, the contrast between DRIPs and non-DRIPs is large (Fig. 7A). DRIPs have a wide range of DOC concentrations, mostly ranging between 18 and 48 mg/l, while non-DRIPs are confined to a range between 0-20 mg/l. Paper II showed that in summer, when dry conditions are common, non-DRIPs have low DOC concentrations (18 mg/l) compared to DRIPs (36 mg/l). These results suggests that during droughts this contrast increases, and groundwater levels in non-DRIPs are not in the upper organic top soil, but predominantly activate deeper soil layers. Meanwhile, DRIPs have been reported to have sustained groundwater-stream connections during extreme low flows (Gómez-Gener et al., 2020), which allow interaction between the organic soil, groundwater, and streams. As such, DRIPs can potentially reduce streamflow intermittence on reach scale, and thereby mitigate effects of droughts on stream water chemistry in headwaters. On network level, the shrinkage of the stream network (Ågren et al., 2015) suggests that headwaters can become disconnected from the rest of the stream network. This adds complexity to the role of DRIPs and headwaters to the scaling of stream DOC patterns further downstream under drought conditions. Potentially, landscape topography can be used to predict where intermittent stream sections are likely to disrupt headwater connectivity with the rest of the stream network (Prancevic and Kirchner, 2019). DRIPs can complement these predictions by locating headwater sections with sustained lateral groundwater inputs, and subsequent increased DOC uptake (Lupon et al., 2019). Together with stream network assessments of stream intermittence and biological processes (Hale and Godsey, 2019), this allows inclusion of hydrological and biological processes in network scale predictions of DOC mobilization under drought conditions.

3.4.2 Rain-dominated conditions

In rain-dominated periods, groundwater levels in non-DRIPs increase, which promotes DOC mobilization in the top soils across the RZ. With the possibility in mind that in DRIPs the routing of rainwater occurs at the surface, it can be assumed that DRIPs can rapidly route event water to the streams through living moss layers. As such, DOC concentrations in DRIP and non-DRIPs are likely to be in a similar range during rain-events compared to droughts (Fig. 7B). However, the moments of near-surface groundwater levels in non-DRIPs are brief, and thereby most of the time DOC concentrations are lower than DRIPs. This is in line with the general perception that DOC concentrations in boreal streams are positively related to streamflow, as a result of groundwater fluctuation.

With increasing export of terrestrial DOC to streams at DRIPs, the local bioavailability of DOC for aquatic microbes increases as well. Because uptake rates of DOC from riparian zones are high (Kothawala et al., 2015; Ledesma et al., 2018a), it is reasonable to assume that with increasing terrestrial export of DOC, the uptake of DOC increases as well. Moreover, DOC uptake rates have been observed to be higher downstream of DRIPs than other stream sections (Lupon et al., 2019). As such, the downstream export of DOC from DRIPs to higher order streams can be overestimated when biological uptake is not considered (Casas-Ruiz et al., 2017).

3.4.3 Snowmelt-dominated conditions

When the snowmelt period starts, snowmelt water is routed towards streams. Similar to rain events, the groundwater level in non-DRIPs rises into the organic top soil, which promotes the mobilization of DOC (Laudon et al., 2004; Lyon et al., 2010). The consistent melt of snow sustains the high groundwater levels. Meanwhile, ice sheets and overland flow at DRIPs can be observed, as shown in paper I. In paper II, the DOC concentrations in DRIPs were reported to be 20% less in spring, compared to other seasons. This suggests that DRIPs convey water which has had less contact with the organic top soil than under rain-dominated conditions, even though groundwater levels are at the surface. During snow-dominated conditions, temperatures are low and biological activity is typically less than in the summer and autumn. Therefore, it is likely that stream DOC dynamics in this period are transport dominated. Bank-full discharge and high flow speeds reduce the residence time of the stream water in headwaters, which further promotes the export of DOC downstream. These conditions reduce variability in DOC concentrations across the stream network (Fig. 7C). However, the spatial variability in snow accumulation, and the subsequent melt can introduce differences in snowmelt response across the catchment. For example, in paper I the lake responded quickly to warm and sunny conditions compared to the forest. As such, open areas can be more exposed to the sun and thereby promote increased snowmelt rates early in the snowmelt period, compared to the forest. Combined with the dilution effect of snowmelt in wetland areas, the snowmelt flood remains a dynamic and heterogeneous hydrological period (Laudon and Sponseller, 2018; Laudon et al., 2011).

3.5 Simulating stream DOC patterns (paper IV)

For the mobilization of terrestrial DOC to streams, DRIPs fill a niche along the gradient of increasing upslope contributing area. However, it remains important to consider other stream water sources, such as non-DRIP RZ, mires and lakes, in the assessment of stream DOC patterns on network level. Furthermore, biological processes can play an important role in the fate of terrestrial DOC once it enters streams. While there are many contributing factors to the spatial variability in DOC concentrations across a stream network, the previous results show that DRIPs fulfill an important role in the landscape when it comes to DOC mobilization. However, it is important to note that throughout different hydrological conditions, the dominant drivers of stream DOC patterns can shift. In paper IV, I focus on two important factors that affect stream DOC: the longitudinal distribution of streamflow contributions along a reach, and the spatial variability in biological uptake of DOC. A model framework was used to simulate longitudinal DOC dynamics along a headwater reach based on these two processes.

3.5.1 Shifting controls on stream DOC patterns

Longitudinal stream DOC observations showed that during various flow conditions, DRIPs affect stream DOC patterns (Fig. 8). Both dilution as well as enrichment of stream DOC concentrations were observed at stream sections where DRIPs connect to the stream. The different simulations showed that both in-stream DOC uptake by biota, and the lateral input of terrestrial DOC can be the drivers of these spatial DOC patterns. During high flow conditions (Fig. 8K-O) the hydrological models that account for DRIPs (UCA_NOBIO and UCA_BIO) were able to represent some of the stream DOC patterns. The inclusion of the DOC uptake by stream biota resulted in improved stream DOC predictions across various flow conditions. Especially in an early summer event (Fig. 8E), the step changes in stream DOC concentrations were accurately represented by simulation of DOC uptake directly downstream of DRIPs (DIFF_BIO). Meanwhile, this simulation did not account for increased hydrological contributions of DRIPs. Under (artificial) drought conditions (Fig. 8G-H), the simulations demonstrated that stream DOC patterns were best represented by diffuse groundwater inputs, without consideration of biological uptake (DIFF_NOBIO).

These findings suggest that riparian areas with high hydrological connectivity, such as DRIPs, are not always hydrologically driving spatial differences in stream DOC (Ambroise, 2004; Klaus and Jackson, 2018). Instead, their hydrological regime influences stream chemistry through deviating groundwater chemistry and local biological uptake. This underlines the importance of representing riparian soil wetness regimes (Kuglerová et al., 2014a; Vidon, 2017), and uptake of DOC (Kothawala et al., 2015; Lupon et al., 2019) in landscape-connectivity frameworks that aim to assess biogeochemical controls of stream ecosystems (Bernhardt et al., 2017).

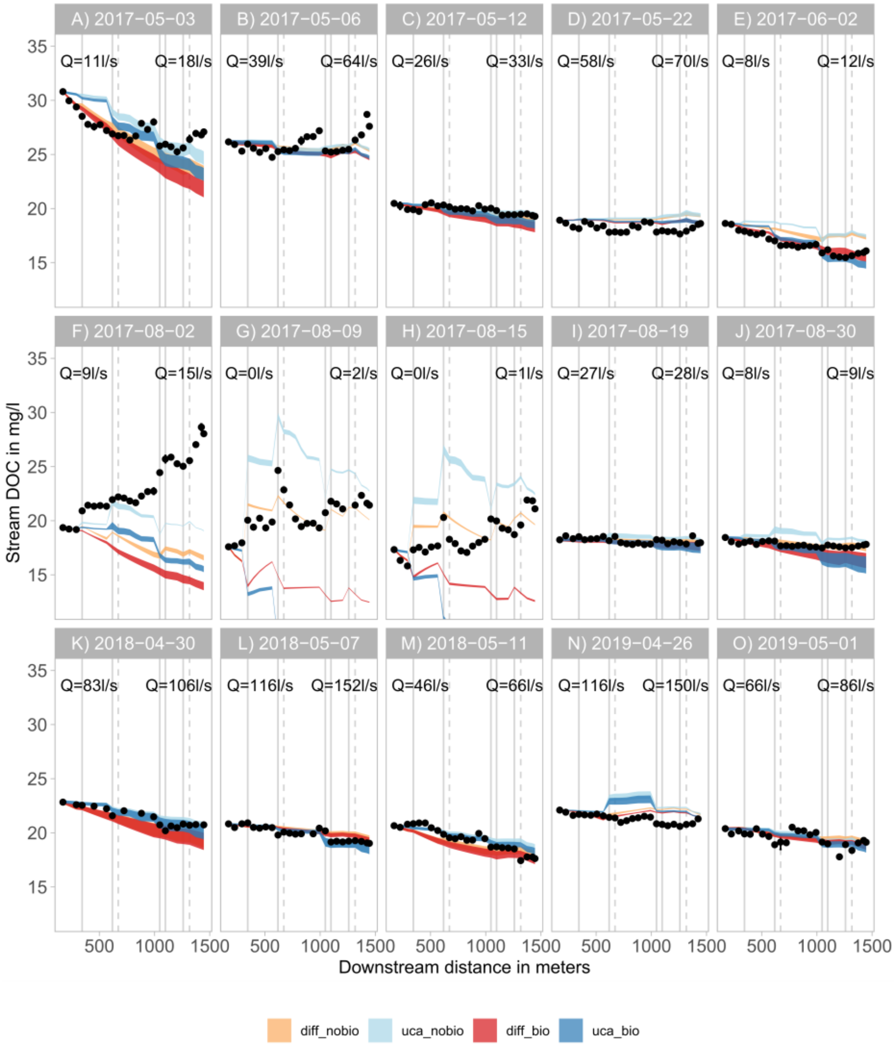

Figure 8 Longitudinal patterns of stream DOC concentrations along the C5-C6 reach. Each panel, indicated by label and date, shows a sampling day. The black dots are the observed DOC concentrations. The colored bands show the simulations of four different models. The vertical grey bars show the locations of DRIPs (solid) and DRIP-like sites (dashed). The streamflow (Q) at hydrometric stations C5 and C6 are shown for each sampling. Figure is obtained from paper IV.

3.5.2 Spatial representation of riparian DOC concentrations

So how much detail is required to spatially represent riparian DOC concentrations? The simulations in the previous sections were based on all the available riparian groundwater data (Fig. 9, level 4), but for future well installations it is useful to know what minimum set of riparian DOC data is needed to represent the spatial variability of riparian DOC concentrations. Figure 9 shows that the variability of simulated DOC concentrations decreased with more spatial detail in riparian DOC concentrations. Representation of DRIPs reduces standard deviations (Fig. 9, level 2), and explicit consideration of individual DRIPs does even more so (Fig. 9, level 3). However, specifying DOC concentrations in the non-DRIP RZ does not gain additional improvements compared to averaged DOC concentrations (Fig. 9, level 4). This shows that besides hillslopes, and streams, DRIPs need to be explicitly considered, on individual level, in assessments of stream DOC patterns along streams.

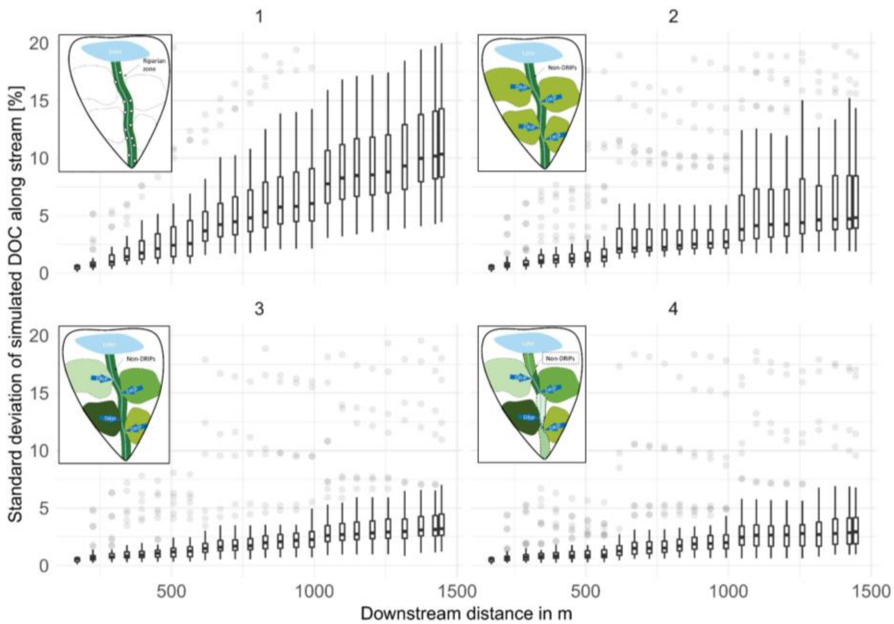

Figure 9 Model standard deviations along the stream reach, using different representations of riparian DOC concentrations. Each panel shows the boxplots of standard deviations of all simulated stream DOC concentrations. The grey dots show outliers. The panel numbers corresponds to the four levels of riparian DOC representation.

4. Conclusions

The goal of this thesis was to understand how groundwater connects the boreal landscape and headwater streams. I have found that DRIPs play an important role in landscape-stream connectivity because they connect large upslope contributing areas with narrow sections of streams. The confluence of subsurface flow paths in DRIPs resulted in contrasting hydrological and chemical regimes compared to the surrounding riparian zone. Groundwater levels were mostly near the surface, and DRIPs had almost double the DOC concentrations compared to adjacent riparian areas. The effect of these contrasting characteristics of DRIPs propagated to the stream. Stream temperature, stream DOC concentrations, and DOC uptake by biota co-varied with the location of DRIPs.

Interactions between groundwater, soil, vegetation and biota can be attributed to these findings. Groundwater levels near the surface have promoted peat accumulation over time. Combined with the large upslope contributing areas, this allows mobilization of DOC from the peat-rich top soils to the stream. The mobilized DOC from DRIPs to streams is partially transported downstream, and partially incorporated in local biological processes. Both in the terrestrial and aquatic system, transport and reaction processes shift in response to changing flow conditions. Under dry conditions, headwaters become discontinuous but DRIPs sustain local groundwater-stream connections. With increasing flow, riparian groundwater tables rise. While in most of the riparian zone this leads to increased mobilization of DOC, at DRIPs overland flow can lead to a dilution effect.

For boreal stream networks, DRIPs fulfill a unique function in DOC mobilization. Hillslope transects represent the small-scale processes, and streams integrate catchments. In between these scales, flow paths converge at DRIPs, resulting in groundwater discharge to narrow sections of stream reaches. For a large fraction of the water in streams and rivers, DRIPs are the last terrestrial environment it has encountered. Therefore, DRIPs need to be considered in riparian forest management, and programs that aim to protect surface water quality. Identification, monitoring, and protection of DRIPs can contribute to the solution of greater challenges, such as mitigating climate change, drought and flood management, and forest and water protection.

5. Future perspectives and application

Here I provide some views on the potential future research directions in relation to DRIPs and the application of DRIPs. I suggest to develop the geomorphological understanding of DRIPs, and I highlight some vulnerabilities in regard of climate change and human activity. Furthermore, I give a perspective on the application of DRIPs in sustainable forest management, and provide a DRIP monitoring strategy.

5.1 Geomorphology of DRIPs

5.1.1 The assumption of mineral soil uniformity

While I argue in the results and discussion section of paper III that the *Sphagnum* peat in DRIPs potentially plays an important role in the generation of runoff to streams during events, I suggest that there is also a potential role for the glacial subsurface during (extreme) low flows. One commonly used assumption in boreal riparian studies is that the mineral subsurface is a uniform, poorly conductive soil layer, compared to the highly conductive organic top soil. However, it is likely that in many real-life examples the mineral soil fraction is more heterogeneous. Although the organic top soil in boreal forests generally has a larger capacity to laterally convey water compared to the underlying mineral horizons, in most parts of the landscape these top soils are rarely activated. Instead, groundwater levels are most of the time in the mineral soil layer. Especially during low flow periods, this is important to consider for assessment of spatial heterogeneity in groundwater-stream interactions.

5.1.2 Glacial subsurface and lateral flow

After the glacier dominated distribution of sediments, the post-glacial period was characterized by erosion and redistribution of sediments (Lindén et al., 2006). Moreover, the discharges from glacial melt were magnitudes greater than in today's hydrological regimes (Stroeven et al., 2016). Given that DRIPs connect relatively large upslope contributing areas with the stream channel, it is likely that flow energy has been higher than in the surrounding non-DRIP areas, but not as high as the stream channel. This suggests that the potential transport of sediment in the post-glacial period, prior to the development of peat-rich top soils, was likely different from the surrounding hillslopes and the stream channels. In addition, Ivarsson (2007) reported that frost on hillslope positions stabilized fine particles and that valley deposits were reworked and received sediments from upslope. As a result, I consider it likely that DRIPs have relatively coarse mineral fractions underneath the *Sphagnum* peat top soil. This would be different from the fine, and consolidated loamy horizons that are typically assumed to underlay the organic top soils. As such, the hydraulic profile of DRIPs might be non-linear, just as the rest of the riparian zone, but in different orders of magnitude of lateral hydraulic conductivity, with a different groundwater regime, and different runoff mechanisms during events. I consider the combination of geomorphology, hydrology, biogeochemistry, and vegetation as a potential direction to deepen our understanding of where DRIPs are positioned in the landscape, and how soil properties affect streamflow contributions.

5.2 Changing climate and human activity

5.2.1 Water storage

The boreal ecosystem is one of the most rapidly changing environments. Increasing temperatures and changing precipitation regimes lead to shorter snow-covered periods, longer growing seasons and more extreme hydrological events (Teutschbein et al., 2015). These changes can alter the snowmelt-dominated hydrological regime. It is likely that this regime is affected in the future by more frequent and more intense rain events, and the intermittent melt of snow in winter. Typically, having a snowmelt-dominated hydrological regime means that after snowmelt (May/June) water storages in the landscape as well as the surface waters are recharged. This provides a certain resilience to drought in the following growing season. I consider it likely that this resilience will reduce as hydrological regimes shift. Wet areas like DRIPs can therefore be important water storages that are “hidden” in the forest. Restoration of DRIPs that have formerly been disturbed by various human activities can therefore increase the drought resilience of forests under future climate conditions.

5.2.2 Carbon storage

The cold and wet soil conditions that have led to the accumulation of peat in DRIPs is potentially compromised by warmer and drier summer periods, and human disturbances. Subsequently, I consider the potential risk that peat-rich, saturated areas in the forest (such as DRIPs) can shift from anoxic to intermittently oxic conditions, both by shifts in climate and human disturbances. This can promote decomposition of peat, which likely enhances mobilization of carbon that has been stored in the subsurface. The key difference of DRIPs compared to any other wet area in the forest, is their direct connection to the stream network. This can facilitate transport of carbon from forest soils to streams, and subsequently to the atmosphere. This ultimately can contribute to greenhouse gas emissions and increased downstream supply of DOC.

5.3 DRIPs in sustainable forest management

5.3.1 Riparian buffer management

Riparian buffers, a strip of untouched land around surface water bodies, of traditionally been based on a fixed width (Buttle, 2002). However, hydrologically adapted buffers that account for local soil wetness conditions have readily been shown to be a more cost effective method to protect riparian zones compared to traditional fixed width buffers (Tiwari et al., 2016). The DRIP concept underlines earlier findings that have shown that considerations of hydrology in buffer management is critical for protection of forest and stream ecosystems (Kuglerová et al., 2014b; Ledesma et al., 2018b). Paper II showed that the majority of the DOC in riparian groundwater is already present 20 meters away from the stream. As such, the width of buffers in the order of tens of meters are likely to be insufficient to protect the vegetation, soil and groundwater conditions that are important for the function of DRIPs. Future research on the upland areas of DRIPs can shed light on the minimum groundwater pathway lengths that need to be respected, to ensure that DRIPs are not impaired by human activity.

5.3.2 Monitoring DRIPs

In order to understand how DRIPs respond to future climate conditions and to explicitly consider DRIPs in forest practices, there is the need to expand the detection of potential DRIPs and monitoring their characteristics. In Figure 10 I suggest a series of steps that can be considered to find and characterize potential DRIPs in headwaters. The provided values in grey are based on the set of DRIPs I encountered, which might differ from others. When assessing the role of DRIPs in a particular setting, it is important to maintain a connection to the processes you are aiming to represent. Moreover, the non-DRIP riparian zone, the stream, and other surrounding landscape features need to be considered as well to contextualize the role of DRIPs in the specific study area. Keep in mind what research question you aim to answer, or what the goal is of the monitoring program. Good luck!

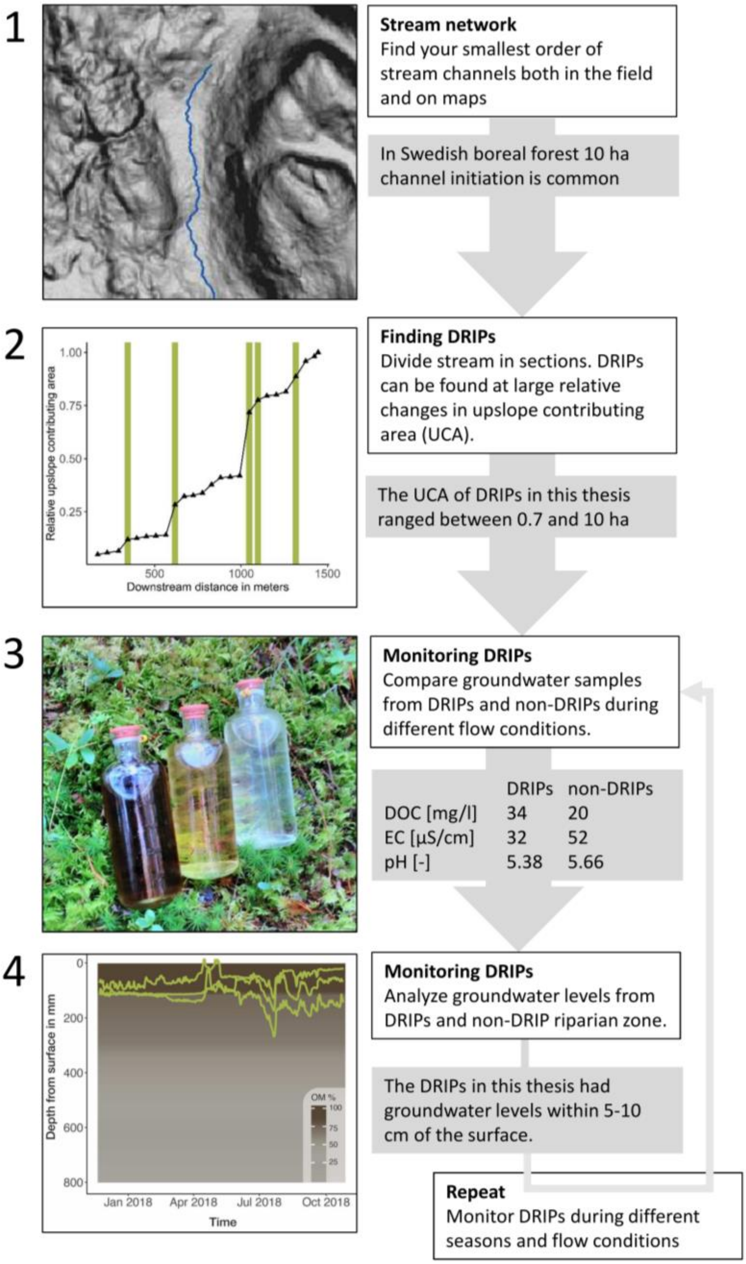

Figure 10 Four steps to detect and monitor DRIPs along a stream reach. Panel 1 shows a stream head. Panel 2 shows UCA along a reach. Panel 3 shows groundwater samples. Panel 4 shows a groundwater level time-series of DRIPs. Panel 2 and 4 are adapted from paper III.

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Popular science summary

To ensure healthy rivers and lakes, it is important to know where river water is coming from. If rivers can be seen as the vascular system of the landscape, small streams are the veins: they are small, but there are millions of them. Groundwater feeds the small streams, often unnoticed and at very slow rates. However, at some places near the stream, groundwater collects before it enters the stream. These places are called DRIPs (discrete riparian inflow points). DRIPs are bad news for hikers and forest machines, as the soil is soft and wet. However, DRIPs are important for river networks. If the streams are the veins of the landscape, DRIPs are the capillaries that connect a large part of the landscape with the streams. This thesis shows that DRIPs are important for biodiversity, carbon transport, and water quality. From dry summers to snowmelt floods, DRIPs play an important role in the routing of groundwater to streams. To ensure healthy streams and rivers, and to sustainably manage forests, it is therefore important to protect DRIPs. Mapping and monitoring DRIPs and small streams can help Sweden to achieve environmental goals such as mitigating climate change, ensure safe drinking water, and protect forest biodiversity.

Populärvetenskaplig sammanfattning

För att säkerställa god vattenkvalitet i våra vattendrag måste vi veta hur de blir till. Som ordspråket säger: många bäckar små gör en stor å. Vattendrag kan sägas fungera som landskapets blodomlopp, men vad är ursprunget för dess vatten? Grundvatten rinner, ofta sakta och obemärkt, nedåt i slutningar och bildar tillslut små bäckar. Men det finns platser kring bäckar dit grundvattnet ansamlas innan det rinner ut. Dessa platser kallar vi DRIPs (discrete riparian inflow points). Det som är så speciellt med dessa DRIPs är att marken är konstant blöt och har låg bärförmåga. Områdena är alltså dåliga platser för skogsmaskiner att kör över, men också för placering av vandringsleder och andra aktiviteter. Men DRIPs är även viktiga för bäcknätverket ur en rad andra anledningar. Om bäcknätverket är landskapets blodkärl, så är DRIPs dess kapillärer. Denna avhandling visar att DRIPs är viktigt för skogslandskapets biodiversitet, koltransport och vattenkvalitet, framförallt under perioder av torka och höga flöden. För att säkerställa god vattenkvalitet i våra vattendrag och en hållbar skötsel av våra skogar, så är det är viktigt att veta var DRIPs är lokaliserade och hur de fungerar. Kartor av markfuktighet, och övervakning av DRIPs och små bäckar kan hjälpa Sverige att säkerställa sina högt uppsatta miljömål, till exempel bekämpa klimatförändringar, skydda biodiversitet och säkerställa dricksvattenkvalitet.

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