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**Key Points:**
- Novel analysis of both short and long term spatiotemporal specific discharge patterns in a boreal landscape
- Changing relationships of catchment characteristics and specific discharge depending on season and hydrological conditions
- Seasonal patterns largely explained by catchment characteristics related to snow accumulation and evapotranspiration

**Supporting Information:**
- Supporting Information S1
- Table S1
- Table S2

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# Landscape controls on spatiotemporal discharge variability in a boreal catchment

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**Abstract** Improving the understanding of how stream flow dynamics are influenced by landscape characteristics, such as soils, vegetation and terrain, is a central endeavor of catchment hydrology. Here we investigate how spatial variability in stream flow is related to landscape characteristics using specific discharge time series from 14 partly nested subcatchments in the Krycklan basin (0.12 – 68 km$^2$). Multivariate principal component analyses combined with univariate analyses showed that while variability in landscape characteristics and specific discharge were strongly related, the spatial patterns varied with season and wetness conditions. During spring snowmelt and at the annual scale, specific discharge was positively related to the sum of wetland and lake area. During summer, when flows are lowest, specific discharge was negatively related to catchment tree volume, but positively related to deeper sediment deposits and catchment area. The results indicate how more densely forested areas on till soils become relatively drier during summer months, while wet areas and deeper sediment soils maintain a higher summer base flow. Annual and seasonal differences in specific discharge can therefore be explained to a large extent by expected variability in evapotranspiration fluxes and snow accumulation. These analyses provide an organizing principle for how specific discharge varies spatially across the boreal landscape, and how this variation is manifested for different wetness conditions, seasons and time scales.

## 1. Introduction

Stream discharge can be highly variable in time and space. These discharge variations are often related to heterogeneity in factors such as weather and climate, geology, vegetation, topography and anthropogenic influences [*Woods*, 2005]. However, the different contributions of these factors and their controls on streamflow variability, as well as their complex interaction, remain poorly understood, particularly in the boreal landscape. Knowledge of how different parts of the landscape contribute to streamflow can further our understanding of how catchments store and release water, which is a key to better management of nutrients and pollutants in stream runoff [*Pinay et al*., 2015].

The heterogeneity and complexity of hydrological systems has been the focus of many studies and has led to great advancements in hydrology, yet we struggle to transfer and simplify this knowledge from one catchment or region to the other [*McDonnell et al*., 2007]. Calls have been made for exploring organizing principles underlying the complexity, classification of catchments and catchment functioning in order to increase our predictive ability with regards to landscape hydrological behavior [*McDonnell and Woods*, 2004; *Sivapalan*, 2005; *McDonnell et al*., 2007; *Wagener et al*., 2007]. One approach to this problem is comparing the variability of hydrological responses in a given landscape, and seeking simple ways of describing this variability at different temporal and spatial scales.

Many studies have explored the relationships between landscape characteristics and runoff generation. A range of approaches have been used, including discharge magnitudes [*Kuraś et al*., 2008; *Payn et al*., 2012], runoff response [*Nippgen et al*., 2011], transit times [*McGuire et al*., 2005; *Soulsby et al*., 2006; *Tetzlaff et al*., 2009], hydrological connectivity [*Jencso and McGlynn*, 2011], water storage [*Sayama et al*., 2011] and variable sources of runoff [*Gannon et al*., 2014]. Specific discharge has been shown to be highly variable in space within boreal meso-scale catchments ($<$ 100 km$^2$) at both short and long time scales [*Nicolson*, 1988;

*Temnerud et al.*, 2007; *Buttle and Eimers*, 2009; *Lyon et al.*, 2012], and the spatial patterns can also vary over time [*Karlsen et al.*, 2016]. Spatial variability of hydrological and biogeochemical processes has been suggested to have different controls that vary with season and wetness states [*Grayson et al.*, 1997; *Buffam et al.*, 2007; *Ågren et al.*, 2014]. *Kuraś et al.* [2008] also found changing patterns between synoptic sampling events, even for similar flow conditions, and specific discharge variability was related to contributing area, flow path velocity proxy, as well as elevation and slope for different periods. *Payn et al.* [2012] found that the influence of topography on spatial base flow variability decreased as streamflow gradually decreased, raising the possibility of increasing influence from subsurface storage characteristics. *Buttle and Eimers* [2009] found landscape characteristics, rather than catchment scale, to be correlated with several runoff metrics, but not annual specific discharge magnitude.

There are, however, hardly any studies on the controls of specific discharge variability which look at both short and longer term patterns, especially not in the boreal landscape. It is particularly important to examine the spatiotemporal variability at the full range of flow conditions and under different seasonal conditions to get as complete an understanding as possible of the landscape patterns [*Woods*, 2005].

This study is based on discharge observations from several subcatchments within the Krycklan catchment in northern Sweden, where specific discharge has been shown to vary considerably in previous studies. *Lyon et al.* [2012] investigated the discharge variability using three synoptic samplings with high spatial resolution. During the driest sampling occasion they found a positive correlation between specific discharge and wetland cover. For the measurements during wetter samplings, no strong correlation with landscape characteristics was found. *Karlsen et al.* [2016] examined the spatiotemporal variability using daily time series from 14 subcatchments in Krycklan and found the spatial variability to be larger during drier conditions and on shorter time scales than during wet periods. In this previous study we found that the variability in specific discharge persists over longer time periods and that spatial patterns are temporally variable. We did, however, not yet explore whether and how this variability might be linked to landscape characteristics and at what seasons and wetness states specific spatial patterns might emerge.

Thus, the main objectives of this study were to investigate links between spatial variation of catchment properties and specific discharge, to determine what landscape patterns emerge at different timescales and wetness states. The following questions were addressed:

1. How does the spatial variability in specific discharge relate to landscape characteristics at different temporal scales, ranging from daily to annual?
2. Are there shifts in these relationships over time, and if so, how are the shifts related to seasonal changes and/or wetness states?
3. What are the dominant controls on discharge variability in this boreal watershed, based on the observed patterns?

## 2. Site Description

The 68 km$^2$ Krycklan catchment is located in the boreal region of northern Sweden (64°25′ N, 19°46′ E), approximately 50 km northwest of Umeå (Figure 1). Forest research began in the catchment about 100 years ago, with water- and geochemistry related research intensifying in the 1980s in the central 50 ha Svartberget catchment. More recently, in 2002, the study area was expanded to the 68 km$^2$ Krycklan Catchment Study [*Laudon et al.*, 2013]. The mean annual temperature and precipitation are 1.8°C and 614 mm, respectively. The monthly mean temperature and precipitation for the study period (2008–2013) and 1981–2013 show higher precipitation in the warmer summer months and in autumn, while winter and spring months have lower precipitation (Figures 2a and 2b; Table 1). About one third of the precipitation falls as snow with a mean annual snow cover period of 167 days [*Laudon and Löfvenius*, 2015]. Snowmelt generally occurs in April–May, resulting in high streamflow for these months (Figure 2c). The terrain is gently undulating, with elevation ranging from 127 to 372 m.a.s.l. The upper altitudes of the catchment are dominated by forest on till deposits (58% of total area) with portions of wetlands (9%), while the lower altitudes are characterized by larger forested areas on silt, sand and glaciofluvial deposits (hereafter sediment soils; 30%). Lakes (1%) and rock outcrops (1%) cover the remaining land surface. Forested area, on both till and sediment soils, covers a total of 87% of the surface, and mainly consists of Scots pine (*Pinus sylvestris*, 63%),

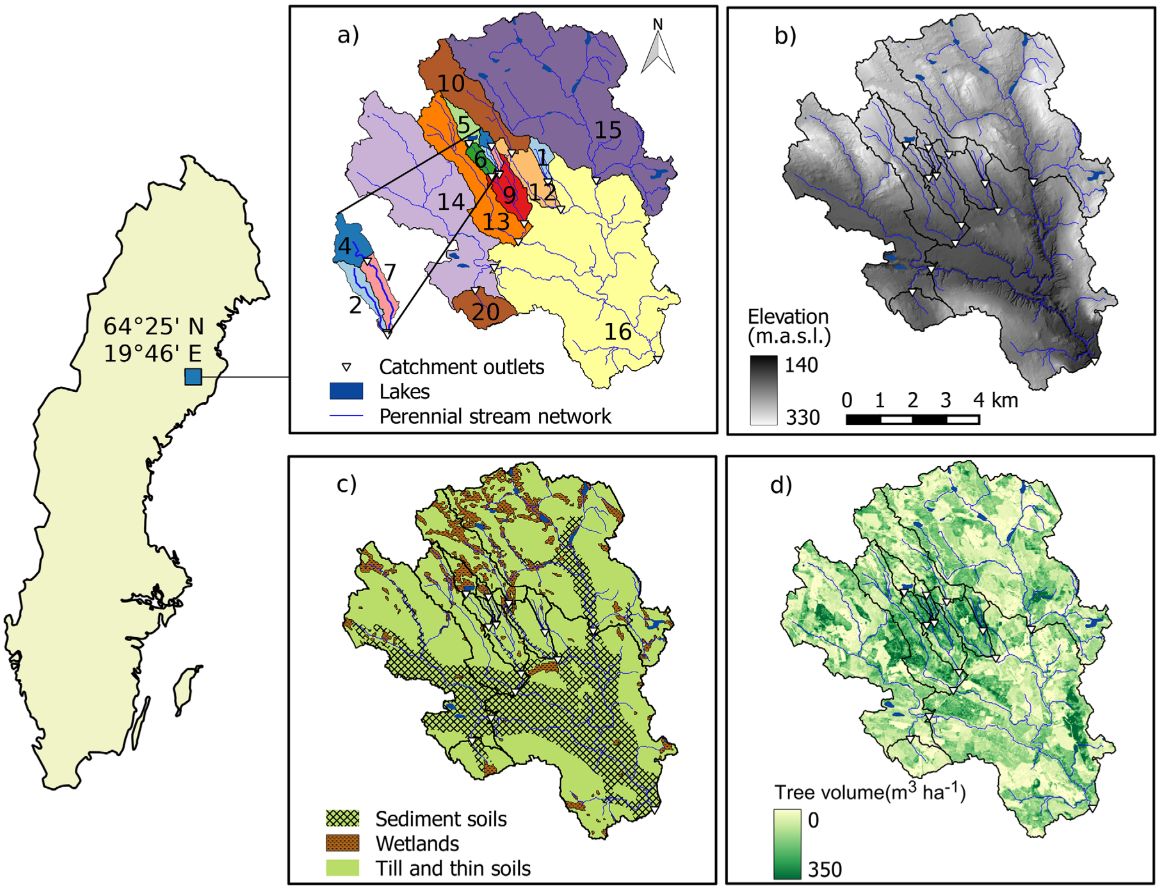


**Figure 1.** The location of the Krycklan catchment in Sweden and catchment maps showing (a) the location of the subcatchments, (b) elevation, (c) Quaternary deposits, and (d) tree volume.

Norway spruce (*Picea abies*, 26%) and birch (*Betula spp*., 10%). Bedrock type shows little variation in the catchment, and is mostly metagraywacke and metasediments (94%).

The streamflow monitoring network used in this study is made up of 14 partly nested subcatchments named C1–C20, including the Krycklan outlet C16 (Table 2 and Figure 1). The subcatchments cover a range of scales from 12 to 6790 ha, and differ in their composition of the different major landscape elements (wetlands, forest on till soils, forest on sediment soils).

Precipitation, snow water equivalent [*Laudon and Löfvenius*, 2015] and climatic variables for Penman potential evaporation (PET) were measured in the central part of the Krycklan catchment at the Svartberget research station (64°14′ N, 19°46′ E, 225 m. a. s. l). While precipitation was only measured at one location

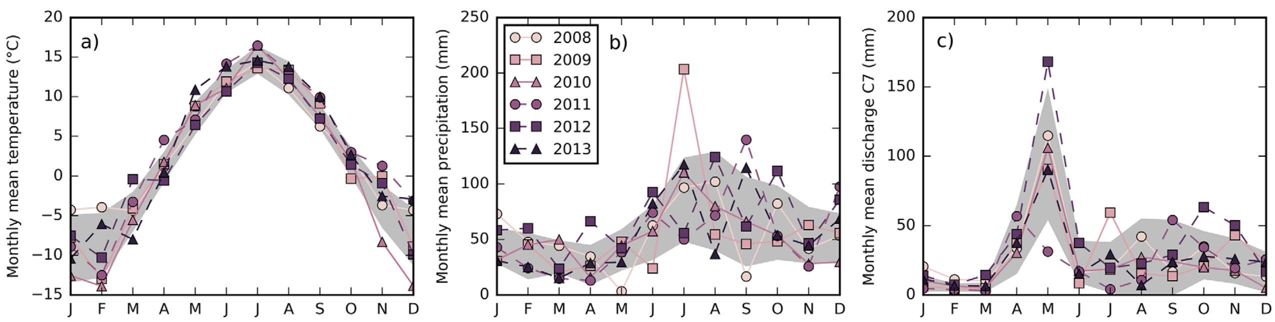


**Figure 2.** Monthly mean (a) temperature, (b) precipitation, and (c) specific discharge at C7 for 2008–2013. Shaded areas show the mean ± standard deviation for 1981–2013.

**Table 1.** Overview of Climate at Svartberget Climate Station in Central Krycklan, and Specific Discharge at C7 for Seasonal and Annual Periods[a]

| Season | Year | P + SWE (mm) | PET (mm) | Q C7 (mm d$^{-1}$) | Q/P C7 | P/PET |
|---|---|---|---|---|---|---|
| Spring | 2009 | 233 | 158 | 2.12 | 0.55 | 1.47 |
| (AM) | 2010 | 259 | 143 | 2.24 | 0.53 | 1.81 |
| | 2011 | 186 | 162 | 1.44 | 0.47 | 1.15 |
| | 2012 | 350 | 106 | 3.47 | 0.61 | 3.31 |
| | 2013 | 220 | 162 | 2.10 | 0.58 | 1.36 |
| Summer | 2009 | 282 | 313 | 0.90 | 0.29 | 0.90 |
| (JJA) | 2010 | 248 | 315 | 0.69 | 0.25 | 0.79 |
| | 2011 | 196 | 346 | 0.34 | 0.16 | 0.57 |
| | 2012 | 272 | 249 | 0.87 | 0.29 | 1.09 |
| | 2013 | 236 | 279 | 0.56 | 0.22 | 0.85 |
| Autumn | 2009 | 94 | 61 | 0.56 | 0.36 | 1.54 |
| (SO) | 2010 | 120 | 52 | 0.72 | 0.37 | 2.29 |
| | 2011 | 193 | 50 | 1.45 | 0.46 | 3.90 |
| | 2012 | 174 | 33 | 1.51 | 0.53 | 5.23 |
| | 2013 | 168 | 37 | 0.84 | 0.31 | 4.53 |
| Hydrological year | 2008/2009 | 676 | 549 | 0.84 | 0.45 | 1.23 |
| (O-S) | 2009/2010 | 668 | 526 | 0.92 | 0.50 | 1.27 |
| | 2010/2011 | 581 | 575 | 0.62 | 0.39 | 1.01 |
| | 2011/2012 | 761 | 415 | 1.19 | 0.57 | 1.83 |
| | 2012/2013 | 725 | 490 | 0.98 | 0.49 | 1.48 |
| 5 year period | Oct 2008 to Sept 2013 | 3411 | 2555 | 0.91 | 0.49 | 1.33 |

[a]For spring season, P + SWE equals precipitation falling within the period in addition to measured snow accumulation (in snow water equivalent) in a clearing in late March [*Laudon and Löfvenius*, 2015]. For other seasons the number corresponds to precipitation measured within the period.

within the catchment, it has been found that long term differences between this gauge and four nearby gauges operated by the Swedish Meteorological and Hydrological Institute (SMHI) are minor (−4.7 to 2.4% [*Karlsen et al*., 2016]), and based on available observations there does not seem to be any significant elevation gradient for precipitation.

## 3. Materials and Methods

### 3.1. Specific Discharge

A daily specific discharge ($Q_{sp}$, discharge per unit catchment area) time series was calculated for each of the 14 subcatchments between October 2008 and September 2013. Observations of water level using automatic stage loggers were possible year-round for four gauging stations in heated houses, and the remaining ten sites were monitored over the ice-free period. Streamflow gauging for rating curve definition was done using salt dilution, velocity-area, and time-volume measurements (total n=325), covering most of the

**Table 2.** Subcatchments Used in This Study and Selected Landscape Characteristics[a]

| Catchment | Area (ha) | Elevation (m.a.s.l.) | Forest (%) | Wetland (%) | Lake (%) | Till and Thin Soils (%) | Sediment Soils (%) | Tree Volume (m$^3$ ha$^{-1}$) | Soil Depth (Depth to Bedrock) (m) |
|---|---|---|---|---|---|---|---|---|---|
| C1 | 48 | 279 | 98.0 | 2.0 | 0.0 | 100.0 | 0.0 | 187 | 12.2 |
| C2 | 12 | 273 | 99.9 | 0.0 | 0.0 | 99.9 | 0.0 | 212 | 9.9 |
| C4 | 18 | 287 | 55.9 | 44.1 | 0.0 | 49.0 | 0.0 | 83 | 10.1 |
| C5 | 65 | 292 | 54.0 | 39.5 | 6.4 | 45.9 | 0.0 | 64 | 12.3 |
| C6 | 110 | 283 | 71.4 | 24.8 | 3.8 | 65.0 | 0.0 | 117 | 9.8 |
| C7 | 47 | 275 | 82.0 | 18.0 | 0.0 | 80.6 | 0.0 | 167 | 11.4 |
| C9 | 288 | 251 | 84.4 | 14.1 | 1.5 | 75.9 | 4.1 | 150 | 14.0 |
| C10 | 336 | 296 | 73.8 | 26.1 | 0.0 | 70.7 | 0.5 | 93 | 9.5 |
| C12 | 544 | 277 | 82.6 | 17.3 | 0.0 | 75.0 | 5.9 | 129 | 12.2 |
| C13 | 700 | 251 | 88.2 | 10.3 | 0.7 | 69.8 | 15.9 | 145 | 13.5 |
| C14 | 1410 | 228 | 90.1 | 5.4 | 0.7 | 53.0 | 38.1 | 106 | 17.3 |
| C15 | 1913 | 277 | 81.6 | 14.5 | 2.4 | 72.9 | 9.5 | 85 | 12.3 |
| C16 | 6790 | 239 | 87.2 | 8.7 | 1.0 | 58.2 | 30.2 | 106 | 16.0 |
| C20 | 145 | 214 | 87.7 | 9.6 | 0.0 | 65.3 | 21.4 | 59 | 15.9 |

[a]See supporting information Table S2 and text for details on characteristics, and supporting information Table S1 for a complete list of the characteristics considered in this study.

observed flow range. Catchment areas for the computation of $Q_{sp}$ from observed discharge series were calculated based on a 5 m resolution DEM derived from airborne LiDAR measurements using the D8 algorithm [*O'Callaghan and Mark*, 1984], assisted by a 0.5 m resolution DEM for questionable areas and field surveys [*Laudon et al*., 2011, 2013]. The daily time series of specific discharge were gap-filled for periods when data from the automatic stage loggers were unavailable, mostly during winter season with ice cover, using the HBV model [*Bergström*, 1976; *Seibert and Vis*, 2012] and the procedure of *Jónsdóttir et al*. [2008] which ensures a smooth transition between the gap-filled and measured data. Further details on stream gauging and gap infilling are found in *Karlsen et al*. [2016].

Catchment 7 has been monitored with a weir in a heated hut since 1981. It has the longest record of streamflow, as well as the fewest data gaps in the study period (2008–2013). For this reason we use discharge from C7 as reference in the presentation of some results to illustrate temporal discharge dynamics. Specific discharge from C7 is, however, not used as a reference in any quantitative analyses.

### 3.2. Landscape Characteristics

#### 3.2.1. Selected Landscape Characteristics

Several landscape characteristics have a potential influence on specific discharge variability. We selected landscape characteristics that both describe different aspects of the catchments, such as terrain, soils and vegetation, and give a good representation of the landscape variability in Krycklan without providing redundant information (summarized below and in supporting information Table S2). A selection of the subcatchment characteristics is shown in Table 2.

The landscape characteristics were calculated within each catchment's drainage area. Slope, elevation, elevation above stream (EAS) and curvature were calculated using the 5 m DEM by taking the average value for each catchment. Slope and EAS is calculated similar to *Seibert and McGlynn* [2007]. Tangential curvature, calculated perpendicular to the slope gradient, was included as a measure of flow divergence and convergence [*Conrad et al*., 2015]. Topographical wetness index (TWI) [*Beven and Kirkby*, 1979] was calculated following *Grabs et al*. [2009]. Median subcatchment area (MSCA), which can be seen as a metric for hillslope and drainage network organization within the catchments, was calculated using the perennial stream network because previous studies have found closer relationships between water residence times and MSCA rather than catchment area [*McGlynn et al*., 2003; *Laudon et al*., 2007]. The ratio between flow path length and gradient to the stream (LFS/GFS) was used as a proxy for hillslope travel time and has previously been found to be related to residence times [*McGuire et al*., 2005]. The proportional cover of soil types was calculated for sediment soils, peat soils (wetland) as well as till and thin soils using soil classification maps from the Geological Survey of Sweden (SGU) (details in *Laudon et al*. [2013]). Wetland and lake area were combined to one class called wet areas following *Lidman et al*. [2014]. Forested areas correspond to land not covered by lakes, wetlands or agriculture (latter excluded here, covers only 2% of total area), and is thus negatively correlated to the sum of these. Catchment average tree volume was chosen to represent vegetation density and is correlated to other variables such as age, biomass and basal area, which were excluded due to strong correlation between these variables (Spearman rank correlation $> 0.94$). Maps of catchment tree volume were based on LiDAR measurement and forest inventory surveys (details in *Laudon et al*. [2013]). Average soil depth was calculated from the SGU soil depth model [*Daniels and Thunholm*, 2014]. Finally, spatially variable potential evaporation, using the radiation and temperature based Turc method ($PET_{Turc}$), and insolation was taken from *Lyon et al*. [2012]. $PET_{Turc}$ was only calculated for 1 year, and scaled to match the PET measured at the climate station, with the purpose of quantifying possible spatial differences in potential evaporation between the subcatchments. The ranked differences in the spatially variable $PET_{Turc}$ were thus assumed not to change between years.

#### 3.2.2. Relating Landscape Characteristics to Specific Discharge

To examine the relation between specific discharge and landscape characteristics we used multivariate principal component analysis (PCA) and univariate Spearman rank correlation ($r_s$) [*Spearman*, 1904].

Due to the strong covariation that often exists between the landscape characteristics a multivariate approach using PCA on the landscape characteristics was applied in addition to univariate analysis. Landscape characteristics were transformed to achieve normality using Box-Cox transformation, scaled for unit variance and mean centered prior to the PCA. The landscape characteristics were also used to create catchment classes or groups through multiple ($n=100$) *k*-means clustering and using the most frequent classification. The principal component (PC) scores were used as independent variables in Spearman rank correlation analysis with spatial specific discharge over a range of fixed aggregation periods of daily, weekly, monthly, seasonal and annual (hydrological year 1 October to 30 September). Seasons were separated into winter (NDJFM), spring (AM), summer (JJA) and autumn (SO) following the Swedish Meteorological and Hydrological Institute for the region [*Vedin*, 1995]. Winter discharge, consisting mostly of modeled gap-filled data, was not used for analysis other than for aggregation periods of annual and longer. Flow duration curves (FDC, cumulative frequency giving the percent of time that a certain specific discharge is equaled or exceeded) were also used to compare specific discharge from different catchments across flow conditions, excluding winter periods.

For the univariate analysis, Spearman rank correlations were calculated between single landscape characteristics and specific discharge over a range of aggregation periods from daily to multiannual, similar to the multivariate approach. The univariate approach was used to complement the multivariate analysis, and highlight the influences of specific landscape characteristics.

## 4. Results

### 4.1. Multivariate Principal Component Analysis

The first two PCs of the PCA for physiographic catchment characteristics explained 37% and 34% of the variation, respectively (Figure 3). These two PCs alone were nontrivial according to the broken stick stopping criteria [*Jackson*, 1993]. The scores of these two PCs were used in further correlation analysis.

Specific discharge was significantly ($p < 0.05$) correlated with either PC at seasonal and annual scales for most periods (Figure 4 and supporting information Figure S1). PC1 gave strong correlations particularly for spring, autumn and annual specific discharge. PC2 was correlated with specific discharge for the summer periods (2010, 2011, 2013), and sporadically for spring (2011), autumn (2009) and annual (2011). The spring (2011) and autumn (2009) periods with lowest correlation between specific discharge and PC1 scores, and highest for PC2 scores, coincided with the lowest observed specific discharge for these seasons. In general PC1 had stronger correlation with specific discharge during relatively wet periods and on annual timescales, and PC2 during relatively dry periods (Figure 4).

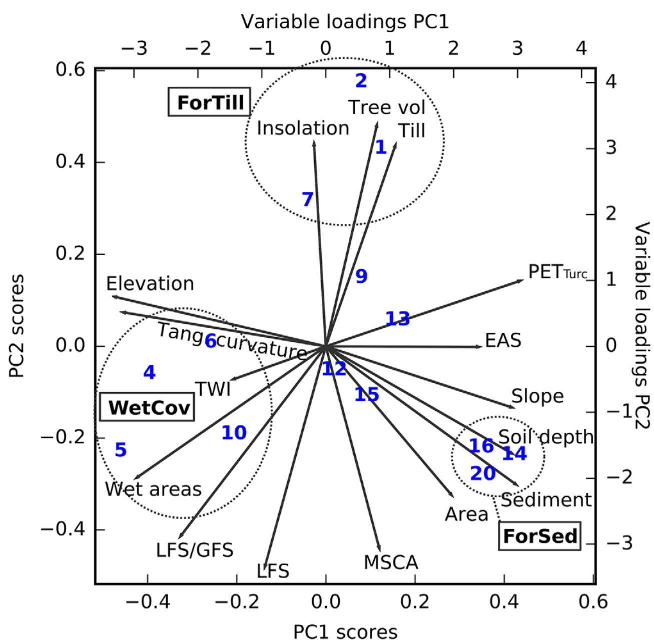


**Figure 3.** PCA biplot of landscape characteristics (labeled arrows) and catchments (blue numbers). The primary axis gives the component scores, and the secondary axis the variable loadings. PC1 explains 37% and PC2 34% of the total variance. Note that specific discharge is not included in the PCA. Circled catchments show the three classifications forest in till (ForTill), forest on sediment (ForSed) and wet areas (WetCov). Remaining catchments are classified as mixed.

Based on the component loadings from the PCA this suggests that during wet periods (PC1) catchments with higher wet area cover (defined as sum of wetlands and lakes) and elevation have higher specific discharge, while areas with higher sediment cover, potential evaporation, deeper soils and larger catchment area have lower specific discharge. It has to be noted that elevation for these catchments is correlated with wet area, as most wetlands are found at the higher elevations, while we did not observe any clear elevation gradient of annual rainfall in the area. During drier periods (PC2) catchments with higher tree volume, potential insolation and till soils cover had lower specific discharge, while areas with high wet area and sediment cover, MSCA and LFS/GFS provided higher specific discharge.

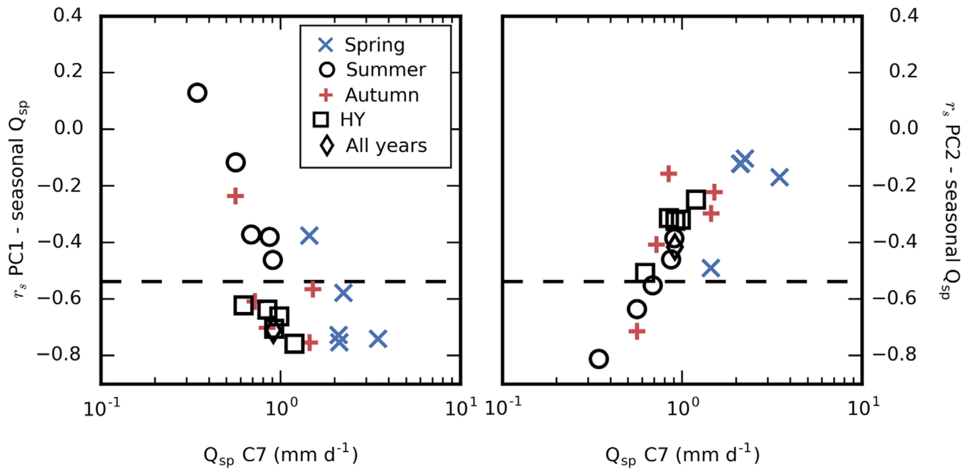


**Figure 4.** Spearman rank correlations ($r_s$) between catchment PC scores (PC1 left, PC2 right) and catchment specific discharges for all years, hydrological years (HY) and seasons. Correlations are plotted against daily mean C7 specific discharge to show variation in wetness state between periods. PC1, related to catchment wet area cover (negatively, −), elevation (−), potential evaporation (positively, +), sediment (+) and deeper soils (+), show stronger correlations for high specific discharge. PC2, related to catchment tree volume (+), potential insolation (+), till soil cover (+), MSCA (−), LFS (−) and LFS/GFS (−), show stronger correlation during low specific discharge. The dashed horizontal line shows the threshold for below which the relationships are significant with $p < 0.05$.

The PCA also helped to understand the correlations between the different catchment characteristics, and was used as a basis for grouping catchments with similar landscape characteristics. The four groups defined were forests on till soils (ForTill; C1, C2, C7), forests on sediment soils (ForSed; C14, C16, C20), high wet area cover (WetCov; C4, C5, C6, C10) and mixed catchments (C9, C12, C13, C15). These groups are identical to the results of multiple (n=100) *k*-means cluster analysis on 4 clusters.

### 4.2. Grouped Catchment Differences

We compared inter-seasonal and inter-annual differences of the ForSed and WetCov against the ForTill catchment group, which served as a reference. To reduce bias we excluded subcatchments C6 and C7 because large proportions of their areas were already included in the analysis in smaller subcatchments (C5, C2, C4). We note that excluding C6 had little or no effect on the results. Excluding C7 increased the differences relative to ForTill (i.e., this group had lowered $Q_{sp}$) mainly during dry periods; however, ranked differences only changed in two cases where the $Q_{sp}$ difference between groups was $< 2$ mm (supporting information Figure S3).

During relatively dry periods both the wetland and sediment catchments have higher specific discharges than forest on till soils (Figure 5). For relatively wetter periods there was little difference between forested till and sediment catchments, while wetlands had higher specific discharges. For example, the difference between forested till and sediment was small during wetter autumns of 2011–2013, and larger during the drier autumns of 2009 and 2010. Nevertheless, the relative differences among catchment types were generally lower during the wetter periods than during the drier periods. When considering all 5 years there was a strong relationship between the seasonal wetness (quantified as P/PET) and difference relative to forested till catchments for both wetland and sediment during summer and autumn, i.e., drier seasons gave a larger difference (supporting information Figure S4). For spring, no pattern was seen with either accumulated snow and precipitation or P/PET ratios for the difference between wetland and till catchments.

There were similarities in flow duration curves for catchments in the same group, and also differences between groups (Figure 6). The forested catchments on till soils had relatively high maximum flows, but lower median and particularly minimum flows compared to other catchments (i.e., they were flashier). Catchments with larger amounts of sediment soils had a flatter flow duration curve, with low maximum specific discharge but relatively high minimum specific discharge. Wetland catchments had the highest maximum specific discharge and also maintained relatively high specific discharge at higher exceedance frequencies, reflecting the high annual specific discharge of these catchments. The mixed catchments (C9, C12, C13 and C15) had similar flow duration curves (not shown), with the first three falling between those

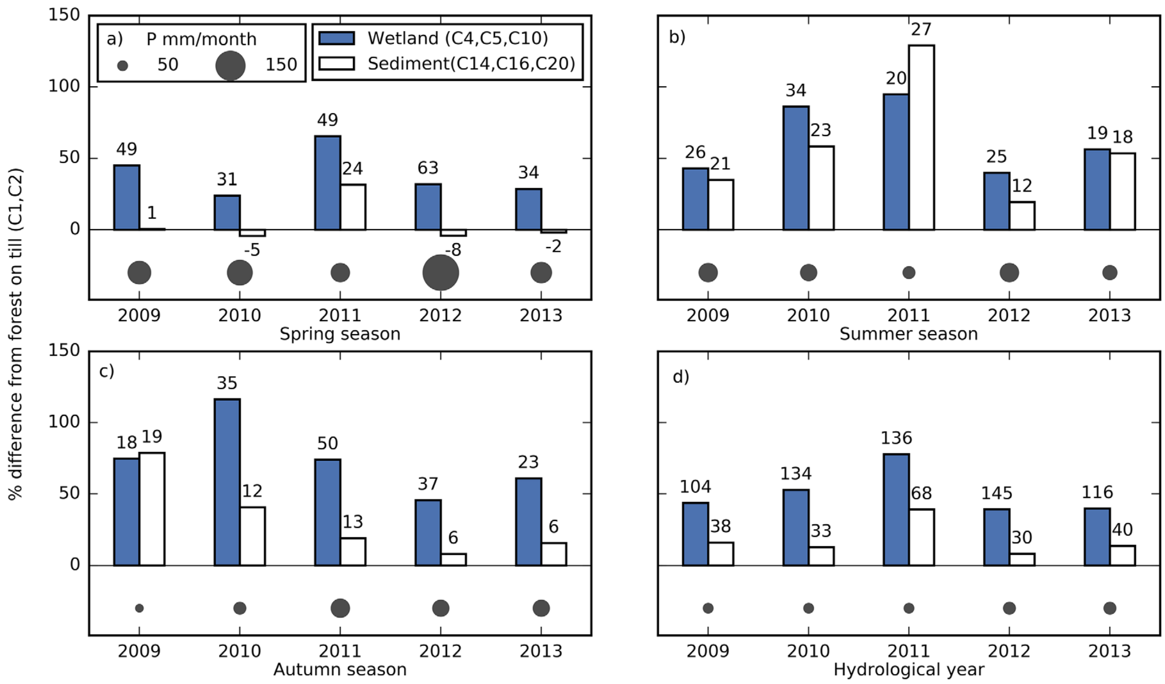


**Figure 5.** Relative difference in mean specific discharge between forest on till catchments and wetland or sediment catchments, for (a) spring, (b) summer, (c) autumn and (d) hydrological year. Absolute difference in mm is given above each bar. Circles below the bars show monthly mean precipitation, including accumulated snow for spring, for each period (cf. Table 1).

of till forests and wetlands and the one for C15 being similar to forest on sediment for low specific discharge.

### 4.3. Univariate Seasonal Correlations

Univariate Spearman rank correlations between landscape characteristics and specific discharge for different seasons and hydrological years showed, just as the multivariate approach did, that landscape patterns of specific discharge changed with season (Figure 7 and supporting information Figure S5).

During the spring season there was a consistently significant positive correlation ($r_s$ 0.58 to 0.83, $p < 0.03$) between the fraction of wet areas covering the catchment and spring season specific discharge (Figures 7 and 8a). Wet area cover was also significantly and positively correlated during other seasons and on annual time scales, but less frequently during summer seasons. During summer, the weakest correlations occurred for relatively dry summers and the strongest for relatively wet summers (cf. Table 1). Other catchment characteristics exhibited similar patterns to wet area, for example the ratio LFS/GFS and catchment elevation. These characteristics were correlated to wet area with $r_s$ values of 0.70 and 0.71, respectively. Catchment tree volume was negatively correlated with specific discharge during summer seasons ($r_s$ −0.65 to −0.76, $p < 0.01$), as well as most of autumn and on an annual basis (Figures 7 and 8b). A similar pattern was seen for spatially variable radiation and temperature

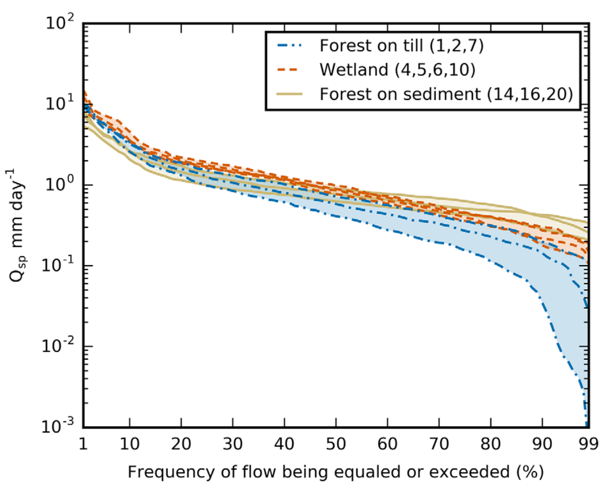


**Figure 6.** Flow duration curves for the catchments grouped based on main landscape characteristics. (Catchments with largely mixed characteristics were excluded).

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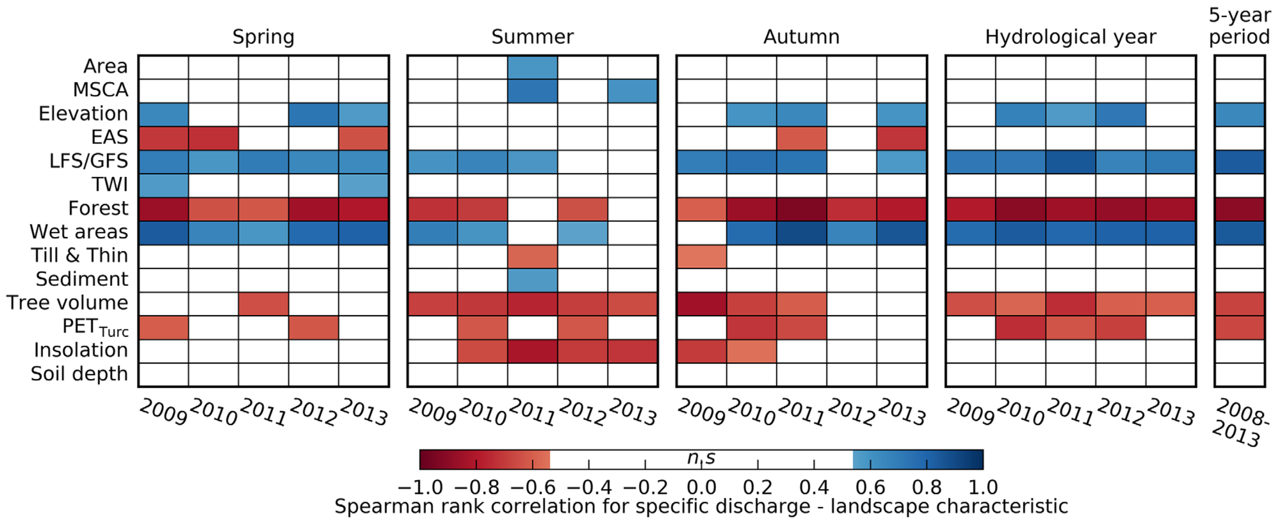


**Figure 7.** Spearman rank correlation between catchment specific discharge and selected individual landscape characteristics. Colors show rank correlation between specific discharge and landscape characteristics for seasonal, annual and the entire 5 year period. White cells indicate nonsignificant correlation ($p > 0.05$). See supporting information Figure S5 for correlations with all landscape characteristics.

based $PET_{Turc}$. The strongest negative correlations with tree volume appeared for periods with relatively low P/PET ratios (i.e., dry periods).

### 4.4. Univariate Correlations Across Temporal Scales and Wetness States

The proportions of sediment soils and related landscape characteristics were not consistently related to the seasonal and long term specific discharge patterns, but were correlated to specific discharge on shorter timescales or during certain conditions. For example, sediment soil cover was only significantly correlated to specific discharge during the summer of 2011 ($r_s$ 0.57, $p < 0.05$), which in turn was the driest of the five summer seasons ($Q_{sp}$ 0.40 mm d$^{-1}$, average all summers 0.66 mm d$^{-1}$). In contrast, when considering finer temporal resolutions there were several occasions where there was a significant relationship between specific discharge and sediment (Figure 9a). These periods lasted up to 2 months, but could also be as short as a few days. The strong positive correlations occurred mostly during the summer season, while shorter periods with strong negative correlations occurred during peak spring runoff and following large runoff

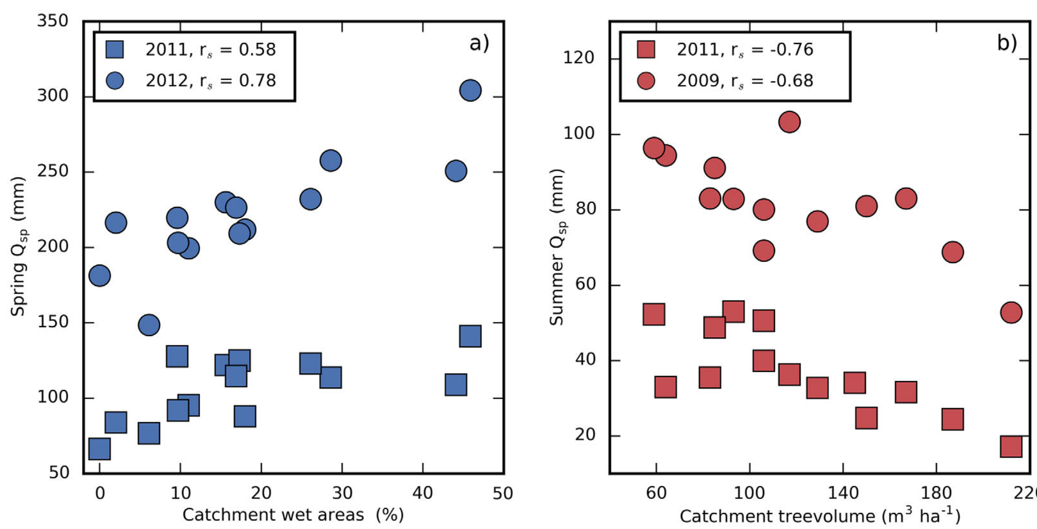


**Figure 8.** Scatter plot illustrating the correlations between (a) wet area (wetland + lake area) cover and specific discharge during spring, and (b) tree volume and specific discharge during summer. Each plot shows the 2 years with the lowest and highest seasonal specific discharge, respectively.

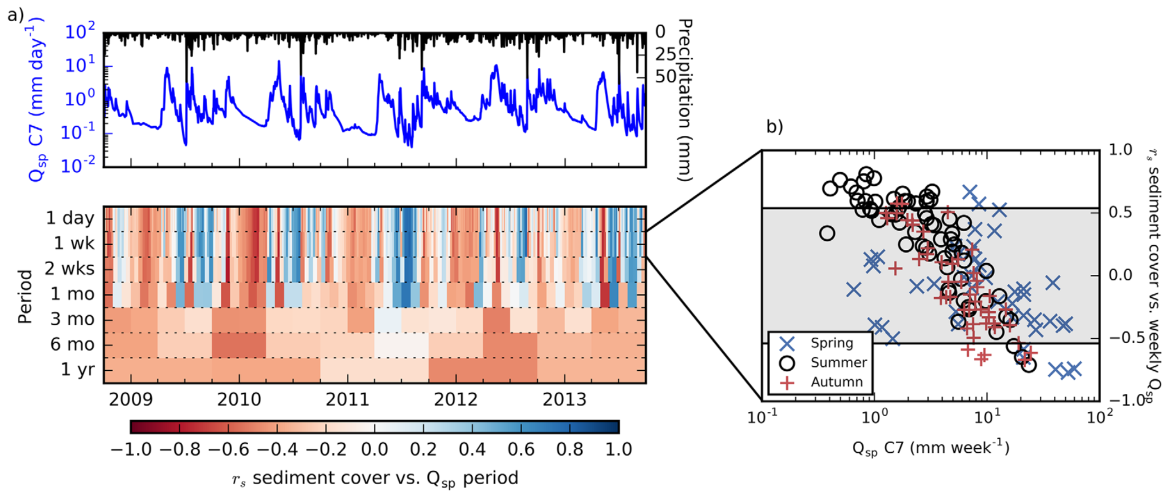


**Figure 9.** (a) (top) Daily specific discharge at C7 (in log-scale) and daily precipitation. (bottom) Time series of Spearman rank correlation between catchment specific discharge and sediment soil cover for different temporal aggregation scales. (b) Weekly Spearman rank correlation for seasons spring-autumn plotted against weekly specific discharge at C7. Grey shaded area denotes nonsignificant correlations ($r_s$ $p > 0.05$).

responses from rainfall events. A relationship was seen for both strength and direction of the correlation with weekly specific discharge magnitudes (Figure 9b). Weeks with high specific discharge coincided with strong negative correlations. As flow levels at C7 decreased, the direction of the correlation gradually changed, and during weeks with low specific discharge, occurring mostly during summer, there was a strong positive correlation between specific discharge and sediment cover. This pattern was stronger during summer and autumn, and less pronounced during the spring months. The same pattern of changing correlation with flow magnitudes was also seen for MSCA, catchment area and soil depth, with a similar trend as for sediment soils.

## 5. Discussion

In this study we have demonstrated that spatial patterns of specific discharge are strongly related to catchment characteristics. These patterns varied depending on season and wetness conditions. During dry periods, catchments with forested areas on till soils had the lowest specific discharge values while catchments with sediment soils maintained the highest specific discharges. This relationship was reversed for the wettest periods. Wet areas showed relatively high specific discharges across all wetness states compared to the other catchments, and particularly during wetter periods with higher specific discharge. The emergence of some of these spatial patterns was only detected by looking at a range of different temporal scales. We found a special value in investigating shorter time scales (days to weeks) as a complement to seasonal and annual patterns, since the shorter time scales provide additional insights into the mechanisms governing hydrological processes in this boreal landscape.

### 5.1. Spatiotemporal Landscape Patterns of Specific Discharge and Associated Controlling Factors

Catchments with similar landscape characteristics had similar specific discharge, and different spatial patterns of specific discharge emerged primarily due to variable wetness conditions. The subcatchment PC scores from the multivariate PCA had a significant correlation with specific discharge at seasonal and annual timescales, and these results were also reflected in the univariate analysis for some of the landscape characteristics. This indicates that the spatial variation in landscape characteristics is strongly related to the spatial variation in specific discharge.

#### 5.1.1. Annual Patterns

On an annual basis, and for the complete 5 year period, there was a strong and consistent positive correlation between specific discharge and catchment wetland area coverage. The wetland areas in Krycklan are known to have a large proportion of event water [*Laudon et al*., 2007] and low mean transit times [*Lyon et al*., 2010] during snowmelt, and they are also a key descriptor of spatial patterns of dissolved organic carbon [*Buffam et al*., 2007] and metal transport [*Lidman et al*., 2014]. Thus, the landscape patterns of wetlands and forests play an important role hydrologically as well as biogeochemically in this landscape. Our results are also consistent with *Lyon et al*. [2012] who found a positive correlation between wet area and specific discharge during one relatively dry period of their synoptic sampling campaigns (mean $Q_{sp}$ 0.56 mm $d^{-1}$). Similarly, *Prepas et al*. [2006] found a strong positive correlation between wetland area and May–October specific discharge over 2 years for nine catchments on the Boreal plain, Alberta, Canada. In contrast, *Buttle and Eimers* [2009] found that catchments on the Precambrian Shield (Dorset Environmental Science Centre, Ontario, Canada) with more wetland and ponds showed a lower ability to maintain low flows, as these landscape elements needed to overcome a storage threshold prior to shedding water. Furthermore, studies in the Northwest Territories, Canada, demonstrated different hydrological functioning of wetlands, and depending on landscape position and connectivity these can either enhance or reduce stream runoff [*Quinton et al*., 2003; *Hayashi et al*., 2004]. The wetlands in Krycklan are mostly located in the headwaters, feeding the downslope streams, and not along the stream valleys as in the Dorset catchments. This indicates a possible changing influence of storage and wetlands on specific discharge depending on the spatial organization, connectivity and geological setting.

The differences in specific discharge which we observed between forest and wetland catchments on an annual basis can largely be explained by the differences in evapotranspiration (ET) that are comparable to elsewhere in the boreal region. Using a simple water balance approach, we estimated the annual average ET flux over the 5 year period for each subcatchment as $ET = P - Q_{sp}$, with P being precipitation measured at the climate station and assumed to have negligible spatial variation on the long term compared to $Q_{sp}$ and ET. Storage changes over the 5 year period were also assumed to be negligible compared to the fluxes. The ratio between actual (ET, from water balance) and potential (PET, as estimated at the climate station) evapotranspiration varied between 0.5 and 0.9, with wetland catchments ranging roughly between 0.5 and 0.6 (ET 250–300 mm $yr^{-1}$) and forest dominated catchments between 0.7 and 0.9 (ET 375–450 mm $yr^{-1}$). These values fall within the ranges of ET/PET ratios for wetlands, and within or slightly above those for forested areas compared to the findings of *van der Velde* [2013], who used a water balance approach and PET estimated from incoming radiation for all of Sweden. The wetland ET/PET ratio also coincides well with the mean ratio of 0.55 found at the Degerö mire using eddy flux methods during the growing season, located only 13 km SW of Krycklan and with similar PET magnitudes [*Peichl et al*., 2013]. *Grelle et al*. [1999] found a ET/PET ratio of 0.69 for a forest near Uppsala, east Sweden. Comparable annual ET (461 and 486 mm $yr^{-1}$) for two forested catchments was found in central Sweden based on water balance [*Rosén*, 1984]. Comparison of ET from forested fen and upland spruce forests in Manitoba, Canada, found that upland forests generally had 10–20% higher ET, although the difference could reach above 50% [*Barker et al*., 2009]. The reason for the relatively low energy efficiency of wetlands has been suggested to be due to higher albedo, both during snow-free and snow cover seasons [*Baldocchi et al*., 2000]; a strong correlation between evaporative fraction and net radiation; and physiological limitations on transpiration by wetland vegetation [*Humphreys et al*., 2006; *Peichl et al*., 2013]. In the boreal region in general, forests have been found to yield higher ET fluxes than wetland areas [*Kasurinen et al*., 2014].

#### 5.1.2. Seasonal Patterns

The variability of ET fluxes will, naturally, also affect the specific discharge on shorter time scales than annual, but other factors such as storage capacity may also play a larger role. For the spring season, there is a strong positive correlation with wet areas and specific discharge (Figure 7), with wetland catchments having 34% higher specific discharge on average (Figure 5). The spatial differences in spring specific discharge can largely, but not fully, be explained by higher accumulation of snow in open wet areas compared to forests. Forests have a large influence on snow interception and accumulation. For example, *Lundberg and Koivusalo* [2003] found that snow interception was related to forest density, and could reach up to 30% of gross precipitation for high density boreal forest. *Pomeroy and Schmidt* [1993] found about 30% higher snow interception and sublimation in winter for pine and spruce compared to a clearing. This is comparable to results from Balsjö (50 km SW of Krycklan) where *Schelker et al*. [2013] observed 27% higher snow accumulation in open compared to forested areas over 6 years.

As a simple thought experiment, based on these published studies we can assume 30% higher snow accumulation in open compared to forested areas. The resulting differences in estimated accumulated snow water equivalent in the wetland catchments compared to the forested catchments amounts to 50–88% of the difference in observed specific discharge (i.e., the differences in observed specific discharge is larger than the estimated differences in accumulated snow). *Rodhe*'s [1987] pioneering applications of isotope hydrograph separation also showed a larger fraction of meltwater in spring runoff from a wetland catchment compared to a forested till catchment in Krycklan. *Laudon et al*. [2007] showed that snowmelt runoff from wetlands is largely event water routed to the streams via overland flow or near surface flow across the frozen wetlands in spring. This runoff mechanism, together with an expected lower storage deficit after winter on wetlands compared to forested till hillslopes (i.e., higher water table [cf. *Kellner*, 2001; *Seibert et al*., 2003, 2011; *Nilsson et al*., 2008]), and the larger amount of accumulated snow, could allow for the higher runoff coefficients observed for catchments with high wetland cover.

For the summer seasons, the differences in specific discharge among the catchment categories are quite small in absolute terms, and smaller than the expected differences from annual ET fluxes discussed above. This suggests either a different spatial pattern of ET fluxes during summer than on the annual scale or that additional effects, such as storage, become more influential. For example, the higher specific discharge observed from forested sediment compared to forested till during the driest summer of 2011 might be a result of storage capacity (discussed further below) and/or differences in spatial patterns of evaporation as the soils progressively dry out. *Betts et al*. [2001] found, in general, similar ET flux dynamics from pine on porous sandy soil and spruce on wetter organic soils, but during dry periods the ET from the pine forest declined due to stomatal control as the soils dried out, while spruce maintained a higher ET. Comparable findings of *Barr et al*. [2009] showed a larger influence of soil moisture and precipitation on ET for pine on well drained sandy soils compared to spruce on wet, poorly drained soils. Hence, spatial patterns of vegetation response to wetness conditions for different soils may be responsible for some of the observed variability. The drier periods might limit vegetation transpiration for some areas, and not for others, creating different patterns in summer, spring and autumn. Differences between all the catchment groups were smaller for the wetter summer of 2012 than the drier 2011. This indicates that inter-seasonal spatial differences in specific discharge are driven by temporal variability in weather, and these differences increase with drier conditions.

The coniferous forest canopy is also capable of intercepting a large percentage of the rainfall. Interception elsewhere in Swedish spruce and pine forests has been reported to reach 30–60% of rainfall [*Grelle et al*., 1997; *Alavi et al*., 2001], and mean rates of 26% have been measured for mature spruce and pine stands in Krycklan over the growing season (Klimat och vattenkemi vid Svartberget – Referensmätning 1981, 1983–1989). Less information exists on interception of short vegetation in the boreal zone, such as wetlands, but it can be expected to be much lower than for forest canopy [*Vajda and Venalainen*, 2005]. Interception losses are not only dependent on canopy structure, but also on meteorological conditions (e.g., rainfall intensity and event size), and spatiotemporal variability can be large depending on these factors [e.g., *Staelens et al*., 2006].

### 5.2. Temporal Variation in Patterns of Specific Discharge

The seasonal and annual analysis can give insight into dominant long term patterns and processes in the landscape, and showed changing patterns of specific discharge among seasons (e.g., summer specific discharge related to tree volume and spring specific discharge to wet areas). When examining specific discharge at shorter timescales, some patterns that were not visible in the seasonal and annual runoff emerged, such as differences between the forested sediment and till catchments which have similar long term specific discharge. The correlation between specific discharge and percentage sediment soils showed a clear pattern with flow conditions (Figure 9b). These correlations are not detectable when considering total seasonal specific discharge due to the relatively low contributions of low flows to the total water export compared to high flow events. The gradual change of the correlation from positive to negative with increasing specific discharge hints that the changes in areal contribution to streamflow between different parts of the landscape is gradual and wetness-state dependent. Changing controls between different periods have also been found by others for specific discharge [*Kirnbauer et al*., 2005; *Kuraś et al*., 2008; *Payn et al*., 2012] and connectivity [*Jencso and McGlynn*, 2011]. The sediment deposits are generally deeper compared to the till soils, and with longer flow paths to the stream network and higher median subcatchment area and catchment area. We therefore see the described pattern here for low flows as not only related to soil type, but also to storage characteristics, drainage organization, flow paths and catchment area. These long flow paths in the lower, more sediment rich parts of Krycklan have been found to result in more base-cation rich, low DOC chemistry and a larger contribution of deep groundwater during base flow periods

[*Tiwari et al*., 2014]. Catchment area has also been found to be important for relative groundwater contributions in Krycklan streams during winter base flow [*Peralta-Tapia et al*., 2015], but not for new/old water ratio during spring snowmelt when landscape elements and median subcatchment area were found to be more important [*Laudon et al*., 2007]. Given the strong covariation between the landscape characteristics, it is difficult to separate factors such as scale and sediment soils with the current data set. As a relatively large reservoir, the deep sediment soils could function as a hydrologic buffer, dampening the flow peaks and increasing base flow through more stable groundwater release [*Knutsson and Fagerlind*, 1977; *Soulsby et al*., 2006; *Santhi et al*., 2008; *Gaál et al*., 2012]. These low flow periods can extend for up to a few months, and can be important for aquatic biota [*Beck et al*., 2013] as well as biogeochemical processes [e.g., *Tiwari et al*., 2014].

Differences among catchment types were clearly reflected in the flow duration curves, where catchments with similar landscape characteristics showed similar response signatures across all flow conditions. Forested till catchments had different flow duration curves (FDC) compared to sediment catchments, with higher maximum and lower minimum specific discharge. The high maximum specific discharge could be a signature of the transmissivity feedback runoff mechanism, which generates fast and high discharge responses when groundwater tables increase in response to snowmelt or rainfall [*Bishop*, 1991; *Bishop et al*., 2011]. The lower minimum specific discharge during summer may be due to the sharp decline in hydraulic conductivity with depth in till soils [*Lundin*, 1982; *Rodhe*, 1989] and transpiration from the denser forests in these catchments.

The relative differences in $Q_{sp}$ between catchment types were often larger during relatively dry compared to wetter periods. On the annual scale this could be explained by ET, which is generally more energy than water limited in Sweden on longer time scales [*van der Velde et al*., 2013]. An increase in precipitation would therefore not have a large impact on ET fluxes, while streamflow would increase and specific discharge would become relatively more similar between the different catchments over longer time scales when storage effects are small. *Peichl et al*. [2013] showed this effect between years for the nearby Degerö mire, where ET remained fairly stable between dry and wet years (~200–300 mm/yr), while stream discharge showed larger variation (~225–750 mm/yr). Variation in ET was not related to water table depth in their study, but rather net radiation and vapor pressure deficit. Similar results were seen for the 32 year data record from C7 in Krycklan, where annual water balance ET was not related to precipitation amount [*Hasper et al*., 2015]. A decrease in precipitation, and ET assumed to be largely energy limited, would therefore result in larger spatial variability in specific discharge given the strong effect of spatially variable ET.

The soil storage characteristics and vegetation could also influence the spatiotemporal patterns of ET and specific discharge. For example during more extreme dry conditions certain parts of the landscape might constrain ET due to water availability while others do not, depending on the soil and vegetation characteristics [*Betts et al*., 2001; *Rodhe et al*., 2006; *Barr et al*., 2009]. This could lead to an increase in spatial variability, as for example observed between forested till and sediment during the drier summer of 2011, but could also reduce variability in other settings. Based on the findings here, an increase in P/PET ratio (i.e., wetter conditions) leads to lower spatial variability for annual specific discharge, while a decrease in P/PET ratio leads to increased spatial variability. Therefore, the climate regime as well as inter-annual weather variability will have a large influence on the spatial variability of specific discharge.

## 6. Conclusions

The annual and seasonal variability among the main landscape types in Krycklan can to some degree be explained by variability in ET fluxes and snow accumulation reported elsewhere in the Nordic and boreal region. An important aspect of catchment functioning that needs to be accounted for to better understand the spatial variability of specific discharge at shorter time scales is water storage capacity and dynamics. The interaction of catchment storage characteristics with discharge behavior remains poorly understood in this landscape, although catchments with deeper sediment soils show the ability to dampen maximum flows and sustain specific discharge during dry periods.

The results show how landscape patterns of specific discharge change during different flow conditions, which needs to be accounted for in studies attempting to regionalize hydrological and biogeochemical processes. Together, the observed patterns provide an organizing principle for how specific discharge varies spatially across this landscape, and how this variation is manifested at different wetness states, seasons and time scales. This organizing principle can broadly be described as follows:

1. Forests on till soils have the lowest specific discharges and show a tendency to dry out faster. High ET gives rise to low annual specific discharge. Shallow groundwater table and the transmissivity feedback mechanism in till-based soils [*Bishop*, 1991] gives rise to flashy hydrologic responses (high maximum $Q_{sp}$), with little storage buffer capacity during drier periods (low minimum $Q_{sp}$).
2. Forests on sediment soils have medium to high ET, resulting in intermediate specific discharge. Greater subsurface storage gives rise to flatter flow duration curves, i.e., high flows are dampened and base flows are maintained through dry periods, relative to forests on till.
3. Wetland areas have relatively low ET, and thus the highest specific discharge overall. A superficial groundwater table together with soil frost during spring gives rise to particularly high specific discharge during wet periods and high runoff coefficients. Base flow is maintained during drier periods due to the low ET and large water storage.

We believe that the processes causing the variability are generalizable to elsewhere in the boreal region. However, the influence that these processes will have on spatial variability of specific discharge will depend on the climate regime and inter-annual/seasonal weather variability together with the spatial organization of landscape elements. The potential for spatial variability in specific discharge to confound the interpretation of catchment biogeochemical export dynamics based on an assumption of uniform specific discharge was highlighted by *Karlsen et al*. [2016]. The patterns defined in this paper confirm this, but also the potential for predicting the specific discharge from landscape characteristics which should allow for more powerful analyses of catchment biogeochemistry based on flow weighted concentrations.

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