Abstract

Nearby catchments in the same landscape are often assumed to have similar specific discharge (runoff per unit catchment area). Five years of streamflow from 14 nested catchments in a 68 km^2 landscape was used to test this assumption, with the hypothesis that the spatial variability in specific discharge is smaller than the uncertainties in the measurement. The median spatial variability of specific discharge, defined as subcatchment deviation from the catchment outlet, was 33% at the daily scale. This declined to 24% at a monthly scale and 19% at an annual scale. These specific discharge differences are on the same order of magnitude as predicted for major land-use conversions or a century of climate change. Spatial variability remained when considering uncertainties in specific discharge, and systematic seasonal patterns in specific discharge variation further provide confidence that these differences are more than just errors in the analysis of catchment area, rainfall variability or gauging. Assuming similar specific discharge in nearby catchments can thus lead to spurious conclusions about the effects of disturbance on hydrological and biogeochemical processes.

1 Introduction

A fundamental trait of hydrological systems is their variability in space and time. This variability is an important driver of both ecological and biogeochemical functions of aquatic environments (Kumar, 2007). Exploring and understanding landscape heterogeneity has also been suggested as an important way to advance our knowledge of catchment behaviour and hydrological predictions (McDonnell *et al.*, 2007; Wagener *et al.*, 2007). Furthermore, to understand how catchment biogeochemistry and water balances respond to changes in land management and climate, it is crucial to acknowledge the variability that may already exist in the landscape (e.g. Teutschbein *et al.*, 2015).

Despite documented occurrence of variability across temporal and spatial scales, it is often assumed that nearby catchments within a similar landscape have similar specific discharges ($Q_{sp,}$ i.e. runoff per unit catchment area). For instance the method of scaling discharge to catchment area, often referred to as the drainage area ratio method, is commonly used to estimate discharge in ungauged catchments (Archfield and Vogel, 2010). This assumption and method is convenient and thus often used in studies that try to discern the influence of disturbance on biogeochemical outputs from catchments and hillslopes where one has measured solute concentrations, but not hydrological fluxes. But if this assumption of similar Q_{sp} is incorrect, the conclusions from such studies could be confounded by the discharge variability between nearby catchments.

Several studies have challenged the assumption of similar Q_{sp} and showed that there can indeed be a large variation in Q_{sp}, even across seemingly homogenous landscapes (Nicolson, 1988; Temnerud *et al.*, 2007; Buttle and Eimers, 2009; Lyon *et al.*, 2012). Most of the studies investigating variability in Q_{sp}, however, have focused on limited time periods, for example synoptic snapshot surveys or time series during baseflow conditions (e.g. Woods *et al.*, 1995; Shaman *et al.*, 2004; Kuraś *et al.*, 2008). As a result of this low temporal resolution it has not been possible to test if the observed variation is a matter of short-term timing in runoff response that could even out over longer timescales. To better understand the nature of the variability of Q_{sp} in the landscape, it is crucial to examine longer time periods. Studies that do cover longer time periods show persistent spatial variability, but have focused either on large catchment scales (100-10,000 km^2) where variation in climate input is large or employed long-term average runoff metrics (Nicolson, 1988; Gottschalk *et al.*, 2006; Buttle and Eimers, 2009; Yanai *et al.*, 2015). The hydrologic community has recently concluded a large effort to increase understanding of the heterogeneity in hydrological response and processes in space and time together with the underlying controls through the PUB initiative (see review in Hrachowitz *et al.*, 2013). However, much of this work has been focused on controls and/or model predictions on large spatial scales, rather than quantifying the spatio-temporal variability in Q_{sp}. Thus, there is a lack of characterization of Q_{sp} variability under similar climate conditions within a meso-scale catchment and across a range of temporal scales. A notable exception is the work of Skøien and co-authors, who did extensive work on space-time correlations and characteristic scales of runoff (e.g. Skøien and Blöschl, 2007).

The lack of space-time distributed data has limited our understanding of the spatiotemporal variability in streamflow relative to factors such as geology, vegetation, topography and climate (Woods, 2005). Variability in Q_{sp} across temporal scales is closely linked to spatial variability, as differences between seasons and wetness states can create different spatial patterns of hydrological processes (Grayson *et al.*, 1997; Payn *et al.*, 2012). Discharge variability has been shown to be a key predictor of catchment solute export variations at both long and short timescales (Seibert *et al.*, 2009; Basu *et al.*, 2010), as well as the functioning of aquatic ecosystems (e.g. Tetzlaff *et al.*, 2005). The variability at short timescales is particularly poorly-documented, but holds the key for quantification of biogeochemical processes and flux budgets where 'hot moments' occur at 'hot spots' in the landscape (McClain *et al.*, 2003; Laudon *et al.*, 2011).

Lyon *et al.* (2012) documented the spatial differences in Q_{sp} between 80 locations in three 'snapshot' surveys across a 68 km^2 forested catchment with relatively small differences in topography, climate and land cover. The ratio between the interquartile range (IQR) and the median of Q_{sp} varied between 37-43%, with changing spatial patterns between the three surveys. However, they based their analyses on instantaneous snapshots of the variability. Thus, the possibility remained that the observed variation was only transient and would quickly average out. Therefore, in this study we determine whether the Q_{sp} variability across the same catchment persisted over longer time periods. We did this by characterizing the magnitude of variability of Q_{sp} across different spatial and temporal scales using daily streamflow from five years at 14 sites. We hypothesised that the spatial variability will even out over longer timescales, and that Q_{sp} differences between catchments will not exceed the measurement errors in Q_{sp}.

2 Material and methods

2.1 Study site

The study was carried out on the Krycklan Catchment, a boreal, meso-scale catchment (68 km^2) (Laudon *et al.*, 2013) located about 50 km northwest of Umeå in northern Sweden (64.23° N, 19.77° E). The climate is characterized by relatively short summers and long winters, with a mean annual temperature of 1.8° C and 614 mm $year^{-1}$ of precipitation. About one third of the precipitation falls as snow and the mean snow cover period is 171 days. Five years of streamflow data (2009-2013) from a total of 14 nested subcatchments with catchment areas ranging from 12 ha to 6790 ha were used in this study (Table 1 and Figure 1). The subcatchments were named C1-C20, with C16 being the catchment outlet. Topography is gentle with elevations ranging from 127 to 372 m.a.s.l., and a maximum mean elevation difference between the gauged catchments of 83 meters with an interquartile range (IQR) of 30 meters. Quaternary deposits found at the higher altitudes are mainly till and thin soils (58 %) and peat (9 %). Postglacial sediment deposits dominate the lower altitudes (30 %), while lakes (1 %) and rock outcrops (1%) cover the remaining land surface. Forests on till and sediment deposits cover 87% of the land surface, mostly Scots pine (63%), Norway spruce (26%) and birch (10%). The variation in the land cover between the gauged catchments as defined by IQR and first - third quartile (in parentheses) of forest cover, wetland area and lake area is 12.3% (75.8-88.1%), 14.2% (8.9-23.1%) and 1.4% (0-1.4%), respectively. Bedrock type in the Krycklan catchment shows little variation, and is dominated by gneissic metagraywacke and metasediments (94%).

2.2 Streamflow data and uncertainty estimation

The discharge monitoring network consists of a partly nested network of 14 catchments including the main outlet. Observations were possible year-round for four gauging stations in heated houses while the remaining ten sites were monitored over the ice free season. Flow measurements for calibration of the rating curves were performed regularly, with more intensive stream gauging during spring and summer seasons when the highest and lowest flows commonly occur. Rating curves are well-defined and discharge measurements were available for most of the observed flow range (extrapolation beyond the highest streamflow gauging was required for 0.4% of the hourly time series on average for all catchments).

Specific discharge (Q_{sp}) was defined as the discharge observed at each monitoring station per unit catchment area. 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) in conjunction with field mapping of catchment boundaries. Questionable sections were further evaluated using a 0.5 m resolution LiDAR DEM. Daily Q_{sp} series were gap-filled using the HBV model for periods where data from automatic stage loggers were unavailable (Bergström, 1976; Seibert and Vis, 2012) with adjustment of the modelled data to ensure a smooth transition to the measured series preceding and following the data gap (Jónsdóttir *et al.*, 2008). Details on stream gauging and gap infilling are found in the supporting information text S1-S2.

Uncertainty in specific discharge measurements were estimated in order to test whether the calculated variability could be a result of data uncertainty. We estimated the uncertainty in both rating curve and gap-filling for the discharge time series, and additionally catchment area uncertainty (set to 5%) for specific discharge. A Monte-Carlo experiment with 10^6 random time series for each catchment was used to test the result of specific discharge uncertainty on calculated variability measures. For more detailed description see supporting information S3.

2.3 Streamflow variability analysis

The spatial variability in Q_{sp} was investigated over a range of temporal scales, from daily resolution to the entire five year length of the dataset. For the temporal resampling, Q_{sp} was aggregated over fixed periods: day, week, month, season and year. Q_{sp} from the subcatchments was compared to the main outlet, C16. The discharge series from catchment C7 was used as a long term reference, as this has been monitored continuously from 1981 in a heated hut, which has allowed for winter season monitoring through-out the monitoring period.

The coefficient of variation (C_V) as well as the ratio between interquartile range (IQR) and the median (C_{IQR}) were used as metrics to describe the spatial variability, including percentage deviation of subcatchment flow from the flow at the outlet (C16). These metrics were summarized for the different aggregation periods using total range and median value. C_V was calculated as standard deviation divided by mean, and IQR as the difference between the 75th and 25th percentile. Q_{sp} was log transformed for the analysis of temporal variability, which allowed the standard deviation (SD_{log}) to be used.

Seasons were divided into winter (NDJFM), spring (AM), summer (JJA) and autumn (SO) following the Swedish Meteorological and Hydrological Institute (SMHI) procedure for the region (Vedin, 1995). The winter season was excluded from variability analysis at higher resolutions than annual, since 79% of these winter days were gap-filled, whereas only 12% of the days from the rest of the year were gap-filled. Spearman rank correlation (Spearman, 1904) was used to assess correlations between catchments for different periods.

3 Specific discharge variability

The average annual flow at the catchment outlet was 317 mm year^{-1}, ranging from 245 mm year^{-1} to 431 mm year^{-1} for individual years during the five year period. Using a 32-year discharge record, which was available for sub-catchment C7 (1981-2013), the hydrological year of 2012 was the second wettest in the 32-year record, while 2011 was the fifth driest. Thus these five years represented much of the spectrum for runoff from this landscape. Average seasonal Q_{sp} for the landscape was 2.4 mm day^{-1} for spring, 0.66 mm day^{-1} for summer, 1.1 mm day^{-1} for autumn and 0.39 mm day^{-1} for winter. Measurement uncertainty estimates for the five year period ranged from ±3 to 12% with an average of ±8% for the 14 subcatchments (Table 1).

For the aggregated five year period, the inter-catchment Q_{sp} ranged from 74% to 135% (C_{IQR} 20%) relative to the main outlet (C16). On an annual temporal scale the Q_{sp} ranged between 61% and 150% (C_{IQR} 19%, Figure 2 and Table 2), showing larger ranges of variability than the estimated discharge uncertainty. Annual C_{IQR} ranged 8-40% when accounting for uncertainty in discharge measurements and catchment area. Seasonal catchment spatial variability was similar to the annual period. Relative to the catchment outlet, spring Q_{sp} varied between 72% and 175% (C_{IQR} 17%), summer between 34% and 130% (C_{IQR} 18%), and autumn between 46 and 175% (C_{IQR} 25%) for the different subcatchments.

The spatial variability increased when moving from longer to shorter timescales (Figure 2, panel a) compared to panel b). Subcatchments with similar long-term Q_{sp} showed strong deviations over periods lasting weeks to months. Weekly flow relative to the outlet ranged from 0% to 248% (C_{IQR} 36%). For example subcatchment C1, which has the most similar long term Q_{sp} to C16 (4% difference), showed weekly variability ranging between 2% and 161% (IQR 50%) compared to outlet Q_{sp}. Thus the short term variability between two sites can be large and alternating, while longer term variability remains stable and small (Figure 3). Rainfall events, in the example of Figure 3, result in particularly high variation at timescales shorter than weekly. During recession periods the differences can remain large over periods of months. All metrics for spatial variability decreased when moving from finer to coarser temporal aggregation periods, with median deviation from the main outlet dropping from 33% at daily scales to 24% at monthly and 19% on annual scales (Table 2).

Furthermore, the spatial variability was consistent between each of the five years, with catchments showing similar relative Q_{sp} compared to each other. The spearman rank correlations coefficients (r_s) between catchment annual Q_{sp} ranges from 0.80 to 0.96 for all combinations of the five year dataset. This illustrates a spatial coherence where the catchments had similar relative Q_{sp} between years. The seasonal flow during spring, summer and autumn also exhibited spatial correlation between years (Table S1) with the strongest spatial correlation for spring Q_{sp} (r_s 0.66-0.97, median 0.82). During summer and autumn the spatial correlation was somewhat lower and exhibited the lowest consistency between years and the lowest correlation with other seasons as well (e.g. r_s for summer vs. spring range from 0.02-0.75, median 0.40). The ranking of the catchments also changed with seasons, i.e., it was not the same catchments providing high and low Q_{sp} when moving from spring to summer. There were weak spatial correlations for seasonal Q_{sp} between spring and summer, while there were strong inter-seasonal correlations (see Figure S1 for an example). Using a higher temporal resolution, for example daily or weekly aggregated flows, variation in ranking appeared more frequently between different periods than when looking at longer aggregation periods.

The spatial variability changed with flow rate. Coefficient of variation (C_V) between sites for weekly aggregated flows below 1 mm day^{-1} varied between 20-110%, mostly occurring during the summer (Figure 4a). The variability gradually decreased as flow levels increased, with a threshold at about 1 mm day^{-1} where the C_V stayed between 15-35% even as flows increased further. At these higher flow levels the C_V approaches the spatial C_V observed for annual Q_{sp} (14-21%). The effect of estimated uncertainty in Q_{sp} on C_V was generally larger for weeks with low flows than for weeks with higher flows. Nevertheless, the pattern of increasing Cv with decreasing flow remain despite Q_{sp} uncertainty. A similar pattern with increasing spatial variability during periods with lower flows exists for other timescales as well, from daily to annual. An almost identical pattern is also seen when considering C_{IQR} as a measure of variability.

The temporal variability (Figure 4b) was higher for the smaller subcatchments across timescales from daily to several months (r_s p-values < 0.1), but not at the annual scale. On a daily scale the temporal standard deviation of log-transformed Q_{sp} (SD_{log}) varied from ~1 for the larger catchments to 1.5 for the smaller ones. This variation decreased for all catchments for longer timescales as a result of temporal averaging, and on the annual scale the SD_{log} varied between 0.15 and 0.3 with no clear relation to catchment area.

4 Discussion

Specific discharge is often assumed similar in nearby catchments. This is the basis for a number of studies looking for factors influencing hydrological and biogeochemical regimes, and estimating discharge in ungauged basins (Emerson *et al.*, 2005; Archfield and Vogel, 2010; Gardner *et al.*, 2011; Judd *et al.*, 2011; Hosseini *et al.*, 2012; Farmer and Vogel, 2013; Lidman *et al.*, 2014; Gianfagna *et al.*, 2015).

A large spatial variability in Q_{sp} was observed between nearby sub-catchments within the Krycklan watershed (Figure 2 and Table 2), showing considerable deviations from previously assumed spatial similarity in Q_{sp} (Ågren *et al.*, 2007). This confirms not only the existence of large variability at the daily timescale (C_{IQR} 43%), but also demonstrated that a considerable degree of variability persisted even over longer time-scales (weekly to multi-annual). Spatial variability remained even after accounting for the estimated uncertainties in specific discharge from rating curve definition, gap-filling and catchment area, rejecting the hypothesis that the variability in Q_{sp} remained smaller than the measurement uncertainties over longer periods in Krycklan. When compared to the published examples across landscapes with a similar span in catchment sizes, the spatial variability for annual flows was higher than that observed at Hubbard Brook (Yanai *et al.*, 2015), similar to that observed at Turkey Lakes, Canada (Nicolson, 1988), but slightly lower than that observed at Coweeta, USA and Gomadansan, Japan (Yanai *et al.*, 2015). In the latter two landscapes the topography was steeper, and at Gomadansan there were recent clearcuts. At daily timescales, the variability observed at the 14 sites in Krycklan was similar to that found by *Lyon et al.* (2012) for instantaneous flows at 80 sites on three separate occasions within the same catchment.

When considering differences between seasons at Krycklan, catchments having high Q_{sp} during spring periods were not the same as those having high flow during summer (i.e. the ranking of catchment flow magnitudes changed between summer and spring). Comparing the Q_{sp} during the summer with the strength of the correlation with spring periods, it was the relatively wet summers that showed stronger spatial consistency with spring flow, while the drier summers showed weaker spatial consistency. This indicates that there was a change in the spatial structure of Q_{sp} depending on the wetness state of the system. These results are analogous to other studies that have also revealed seasonal and wetness dependency of hydrological and biogeochemical processes (Grayson *et al.*, 1997; Buffam *et al.*, 2007; Payn *et al.*, 2012).

The between site variability showed a larger range at shorter temporal scales, e.g. the median C_{IQR} for weekly periods was 36%, compared to 19% for annual timescales. This increase of variability observed at shorter timescales was strongly related to the magnitudes of flow (Figure 4a), with a strong increase in variability below 1 mm day^{-1}. At higher flow rates the relative variability, even at shorter timescales, approached the range observed between hydrological years. Days with higher flow rates than 1 mm day^{-1} occur 25% of the time, but contribute to 69% of the total Q_{sp} at C7. The spatial variability seen during relatively low flows, which dominate in duration, was higher compared to that observed for periods of higher flow which dominate water export. A possible explanation for the larger differences between sites during the drier periods, observed across timescales, can be that the landscape differences in snow accumulation, evapotranspiration, and storage-release of water are enhanced as the landscape becomes drier. *Jencso and McGlynn* (2011) found that vegetation and geology influenced landscape-stream connectivity (and runoff magnitude) more during drier periods, while topography was more influential during wet catchment states. The larger magnitudes of evapotranspiration during the summer season can also result in higher variability in the water balance between various parts of the landscape when streamflow is low compared to seasons when evapotranspiration is much lower relative to streamflow (e.g. autumn and winter).

The range of temporal flow variability observed at Krycklan at the annual scale is comparable to what was observed at Hubbard Brook, USA, Coweeta, USA and Gomadansan, Japan (Yanai *et al.*, 2015). At the annual scale there was no relationship between year to year variability and catchment area. The temporal variability, however, increased with decreasing catchment area for shorter timescales from months to days (Figure 4b). Similar patterns of increasing variability at smaller scales have been observed for streamflow (Woods *et al.*, 1995), water residence times (Soulsby *et al.*, 2006) and chemistry (Asano and Uchida, 2010). This has been attributed to the larger catchments integrating the larger variability observed at smaller scales. Another potential control on the variability in streamflow is subsurface characteristics (e.g. Genereux *et al.*, 1993) or complex interactions between processes and scaling (Blöschl and Sivapalan, 1997). The role of these factors at Krycklan has yet to be explored.

4.1 Sources of error

Errors are present in all measurements, and main error sources that could be contributing to variability in Q_{sp} were considered to be discharge time series and catchment area. Catchment area will give persistent, systematic errors which would be reflected most clearly in the cumulative five year discharge. If long-term Q_{sp} was indeed uniform, this implies errors of 4 to 35% (median 15%) in the definition of catchment area. Such errors are larger than are typically reported for uncertainties for non LiDAR-based catchment areas (CV 0.7-1.3%, Lindsay and Evans, 2008) and using LiDAR (0-5%, Yanai *et al.*, 2015). If assuming long term uniform Q_{sp} by scaling catchment areas (c.f. text S3), short term variability is only slightly reduced (e.g. median C_V of 35% to 30% at the daily scale, Table S2). The weekly relative difference of the scaled time series (Figure 2 panel c) shows little difference in the ranges of variability compared to the measured, unscaled time-series (Figure 2 panel a). Error in catchment delineation would also not explain shorter term differences or seasonal patterns, and especially not the differences between seasons in catchment flow rank. *Lyon et al.* (2012) also showed that uncertainty in catchment areas was unlikely to produce the variability in patterns they observed in Krycklan for instantaneous flows.

Uncertainty in the discharge time series was assumed to be caused mainly by errors in rating curve definition and gap-filling (cf. text S3). We consider the rating curve error to be largely constant, like catchment delineation errors, and therefore not responsible for the variability seen where the spatially ranked Q_{sp} changes between seasons (e.g. spring to summer). The calculated spatial variability also remained when considering both the uncertainty in discharge time series and catchment area (5%) on both weekly (Figure 4a) and annual timescales.

Additionally, spatial variability in precipitation can result in Q_{sp} variability. Five precipitation gauges outside the catchment operated by the Swedish Meteorological and Hydrological Institute show little long term variation compared to the Krycklan rain gauge (-4.7 to 2.4%) and no elevation or spatial gradient (Text S3 and Table S3). However, at the shorter term (e.g. daily to monthly) precipitation shows larger variation in space, but without systematic bias (Figure S2). This will contribute to variability in discharge, and can be seen as one cause of short-term variability in Q_{sp}, rather than an error. This precipitation variability will, however, be random and decrease as the temporal aggregation increases. Short term precipitation variability in space of a random nature is not believed to create the consistent spatial and seasonal differences that we have observed in Q_{sp}.

4.2 The variability is real – and a source of information to be interpreted.

Here we have shown that the spatial variability of Q_{sp} across a landscape remains at long timescales and its magnitude depends on the temporal scale. The variation in the annual median C_{IQR} ratio was 19%, and became progressively larger when moving to seasonal (17-

25%), monthly (25%), weekly (36%) and daily (43%) scales. This is consistent with the variability of 37-43% previously reported from synoptic campaigns (Lyon *et al.*, 2012). Given that measurement errors are not the main source for much of the observed variability in Q_{sp}, we reject the assumption that Q_{sp} can be considered similar across boreal landscapes until there is an even greater degree of similarity than that found in the Krycklan basin.

The observed variabilities are on the same order of magnitude as predicted changes in runoff due to climate change at the end of this century, or the observed effects of clear-cutting large portions of forested catchments in the region. Climate change effects on runoff are predicted to give increases of annual flows from about 10-30% for the region (Andréasson *et al.*, 2004; Teutschbein *et al.*, 2015). Clear-cutting experiments in the boreal region have shown increases in annual runoff of about 35% (Sørensen *et al.*, 2009) and 20% (Ide *et al.*, 2013) in the years after harvest. This highlights the importance of quantifying the present day spatial and temporal variability in Q_{sp}, in order to better inform our models when studying effects of future perturbations. The variability in Q_{sp} also has implications for studying variability of solute exports in the landscape, since assuming spatial and temporally uniform Q_{sp} may introduce significant errors in solute export estimates and predictions.

It is important to note that despite the large spatial variability in Q_{sp} and lack of correlation between catchment scale and annual Q_{sp} (r_s -0.29 to 0, p-values > 0.3), there is a strong correlation between catchment area and volumetric discharge ($[L]^3[T]^{-1}$). For example, mean summer volumetric flow rates are correlated to catchment area ($r^2 > 0.99$) for all five summers. This metric has been used as an argument to scale Q_{sp} to ungauged landscapes and validate runoff models (e.g. Darracq and Destouni, 2005; Gardner *et al.*, 2011; Judd *et al.*, 2011), despite the possibility of being a poor measure of uniformity of Q_{sp} as shown by Wrede *et al.*(2013).

At short timescales, such as sub-weekly, large differences in Q_{sp} are often the product of different responses in both discharge magnitude and timing to rainfall. Based on the random nature of precipitation variability at gauges surrounding Krycklan on shorter timescales, we hypothesize that the spatial variability in precipitation can also result in random variability in Q_{sp}. This is likely to be related to the nature of the precipitation as well, with convective storms typically having shorter and smaller characteristic time-space scales than frontal systems (Blöschl and Sivapalan, 1995). The spatial variability in streamflow response to precipitation can be seen as a result of how different catchments filter these inputs through different stores (surface storage, soil moisture and groundwater) and the mechanisms that in turn produce stormflow and baseflow. The subsequent streamflow recession can result in differences over several weeks. For longer timescales the discharge variability due to spatial precipitation variability evens out, since the spatial precipitation variability evens out (Figure 2 and Figure 3). Thus we believe that much of the spatial variability in Q_{sp} can be related to spatial differences in evapotranspiration, snow accumulation and subsurface characteristics, especially when moving beyond daily to weekly timescales. For example, during different subsurface storage conditions the variability in which parts of the landscape are connected and contributing to streamflow can be large (Jencso and McGlynn, 2011).

As much as 90% of total stream length in Sweden has been shown to have catchment areas below 15 km^2, and many local management decisions are made on this scale (Bishop *et al.*, 2008). Most of the connectivity between streams and landscapes occur in these smaller headwaters, which are important for determining stream water quality and ecosystem services. Given the greater variability in Q_{sp} between smaller catchments, we argue that it is particularly important to measure and understand the variability observed at smaller scales. Acknowledging this spatial variability in Q_{sp} is needed at the very least to avoid misinterpretation of biogeochemical processes, such as the contributions from wetlands or forests. The apportionment of catchment source areas for surface water constituents based on the concentration differences and timing of outputs from different parts of a larger basin is vulnerable to errors in the estimate of discharge from the different parts of the basin. Ignoring the variability in Q_{sp} will thus confound interpretations of hydrological and biogeochemical processes in the landscape.

The spatial variability of discharge is, however, also a source of information from which we can seek further understanding of the landscape structure in hydrological response and catchment functioning (e.g. Skøien *et al.*, 2003; Buttle and Eimers, 2009). This is a valuable basis for improvements in hydrological and biogeochemical modelling, as well as the extrapolation of such models in space and time, as for example in predictions for ungauged basins and catchment classification (McDonnell and Woods, 2004; Sivapalan, 2005).

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Table 1. Catchment gauging setup and characteristics. See *Laudon et al.* (2013) for further details on catchment characteristics. $\varepsilon_{5\text{-year}}$ is the estimated uncertainty in the discharge timeseries for the five year period. PT: MJK 3400 pressure transducer with Campbell Scientific CR1000 data loggers, TT: TruTrack WT-HR 1000 capacitance rods, Float: OTT model X float operated strip chart recorder, Radar: bridge mounted OTT RLS Radar.

Catchment	Gauge type	Area (ha)	Elevation (m.a.s.l.)	Forest (%)	Mire (%)	Lake (%)	Infilled Q (%)	Infilled days (%)	$\varepsilon_{5\text{-year}}$ (%)	Water level loggers
C1	90° V-notch weir	48	279	98.0	2.0	0.0	9	33	6	PT, TT
C2	90° V-notch weir[1]	12	273	99.9	0.0	0.0	18	37	8	PT, TT
C4	90° V-notch weir[1]	18	287	55.9	44.1	0.0	11	32	7	PT, TT
C5	120° V-notch weir, H-flume[2]	65	292	54.0	39.5	6.4	8	36	6	PT, TT
C6	Culvert	110	283	71.4	24.8	3.8	13	33	5	PT, TT
C7	90° V-notch weir[3]	47	275	82.0	18.0	0.0	4	13	3	PT, TT, Float
C9	Culvert	288	251	84.4	14.1	1.5	22	45	7	PT,TT
C10	Culvert	336	296	73.8	26.1	0.0	24	46	12	PT,TT
C12	Venturi flume	544	277	82.6	17.3	0.0	37	50	9	TT
C13	Trapezoidal flume	700	251	88.2	10.3	0.7	24	52	10	PT,TT
C14	Natural section	1410	228	90.1	5.4	0.7	33	52	11	TT
C15	Natural section	1913	277	81.6	14.5	2.4	18	46	6	PT,TT
C16	Natural section (bridge)	6790	239	87.2	8.7	1.0	18	43	9	TT,RADAR
C20	Culvert	145	214	87.7	9.6	0.0	27	45	11	TT

[1] Heated since 2011
[2] Heated H-Flume installed 2012
[3] Heated since 1981

Table 2 Summary of spatial specific discharge variability for different aggregation periods. Note that annual metrics include infilled winter flow, other aggregation periods do not.

Aggregation period	Range relative to outlet (C16)	Median absolute deviation from outlet (C16)	median C_V	median C_{IQR}	median Q mm day^{-1}	mean Q mm day^{-1}
Day	0-414%	33%	35%	43%	0.72	1.28
Week	0-248%	30%	31%	36%	0.81	1.27
Month	11-205%	24%	24%	25%	0.92	1.29
Spring	72-175%	20%	17%	17%	2.22	2.42
Summer	34-130%	14%	16%	18%	0.67	0.66
Autumn	46-175%	24%	22%	25%	0.93	1.06
Annual	61-150%	19%	18%	19%	0.88	0.91

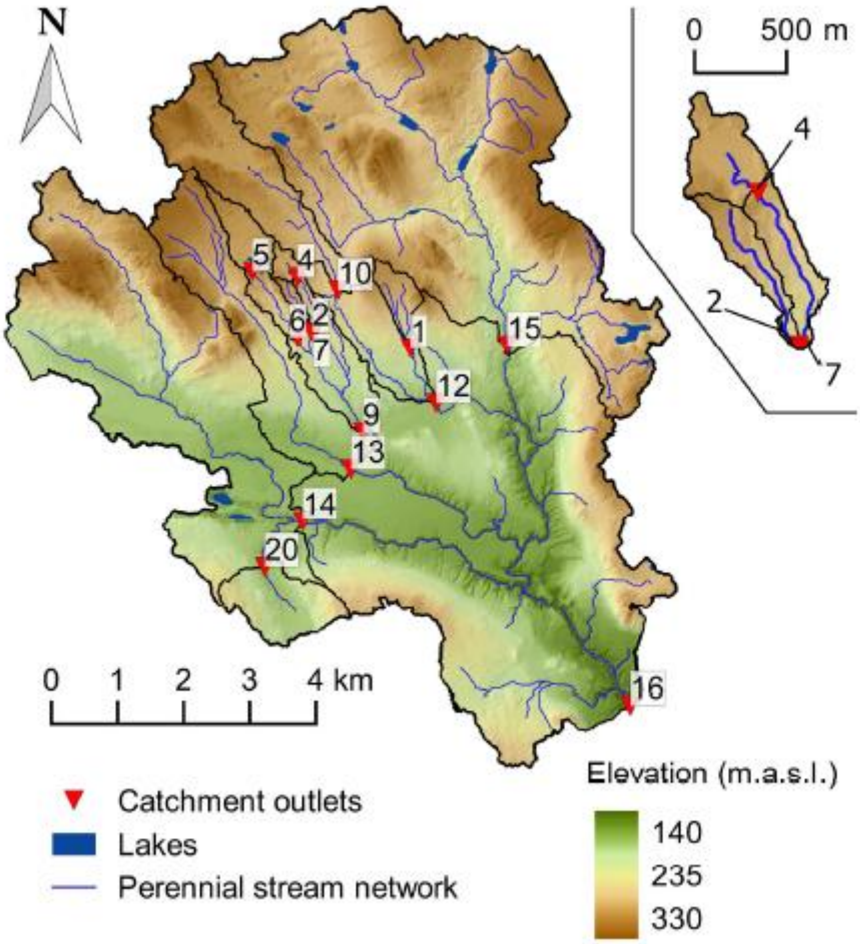

Figure 1: Map of the Krycklan catchment showing the location of the subcatchments and elevation.

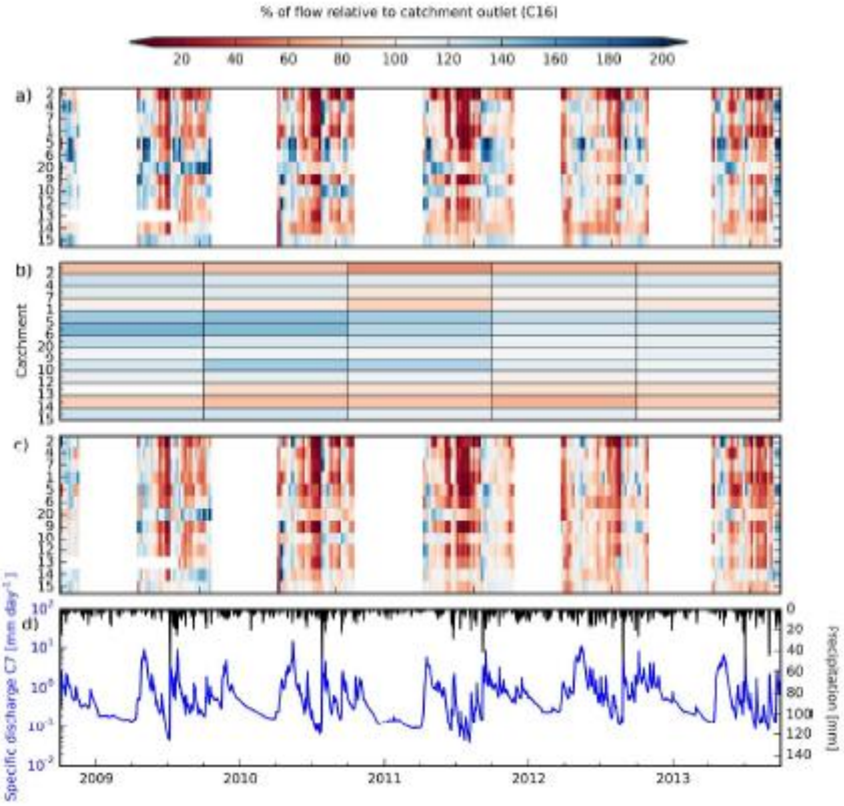

Figure 2: Temporal variability in percentage flow relative to the main outlet (C16) for a) weekly aggregation, b) annual aggregation (hydrological year) and c) weekly aggregation where catchment areas are scaled to yield uniform specific discharge in the five year aggregation of catchment flows. Blank periods in panel a) and c) indicate ice periods where infilling is required. Catchments on the y-axis of panel a)-c) are sorted by increasing catchment area. The lower panel shows specific discharge at C7 and precipitation.

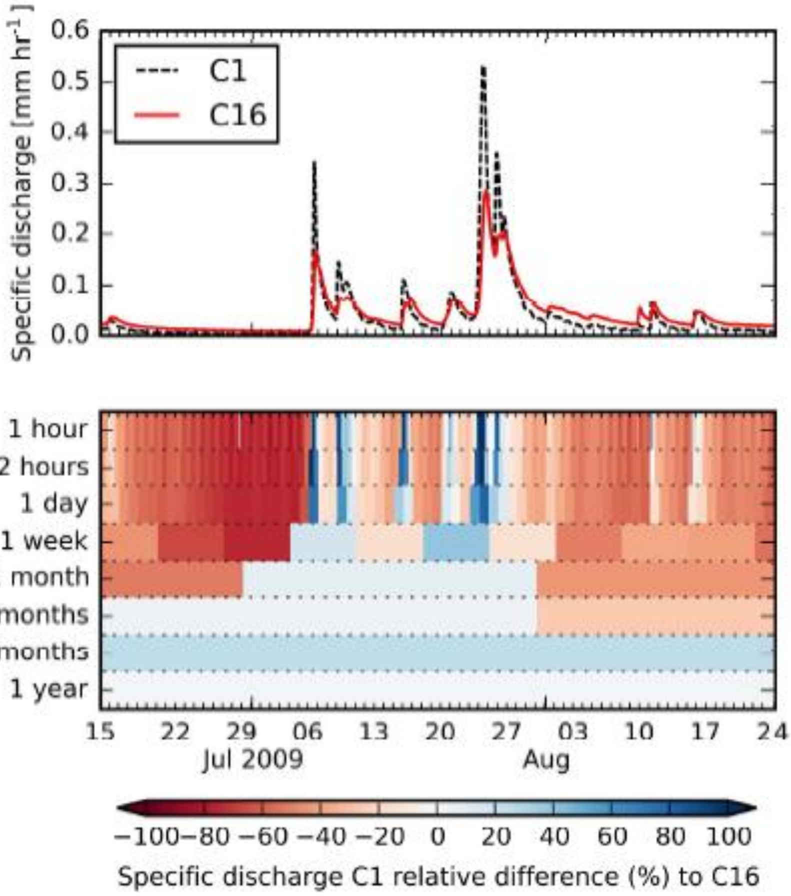

Figure 3 Temporal variability in the deviation between C1 and C16 during the summer of 2009 for different aggregation periods. On shorter timescales the deviation is strong, while on longer timescales it gradually evens out. These two catchments have similar long term specific discharge.

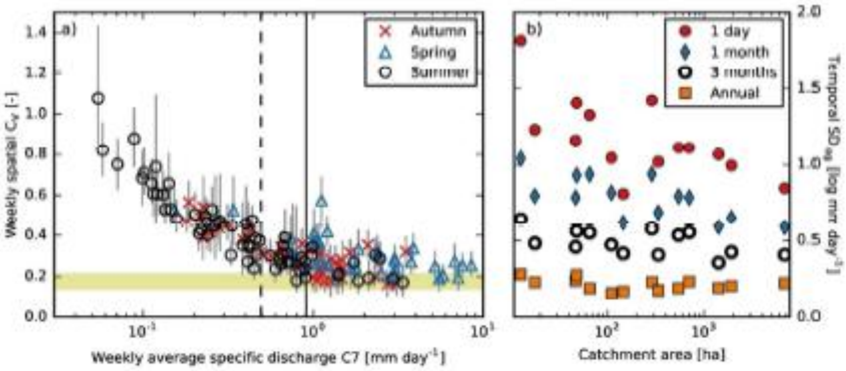

Figure 4 a) Spatial coefficient of variation (CV) and standard deviation of weekly aggregated flow for different flow levels. The high value during spring falling above the point cloud was from the beginning of the melting period. Horizontal shaded area shows the range of CV for the different hydrological years. Error bars show the minimum and maximum calculated CV when considering uncertainties in discharge and catchment area (details in text). Vertical bars show the median (dashed line) and mean (solid line) specific discharge at C7.
b) Temporal standard deviation of log-transformed specific discharge against catchment area for each catchment, aggregated over daily, monthly, quarterly and annual periods. Spearman rank correlations between catchment area and SDlog are significant ($p < 0.1$) for daily to quarterly aggregation, while annual variability is not significantly related to catchment area ($p = 0.45$).