The Assumption of Uniform Specific Discharge: Unsafe at Any Time?

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Abstract

A mainstay of hydrology is that nearby catchments with similar land cover and topography are 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. 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. Systematic seasonal patterns in specific discharge variation provide confidence that these differences are more than just errors in the analysis of catchment area, rainfall variability or gauging. Assuming similar runoff in nearby catchments could 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 predictions in ungauged basins (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.

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). 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 used in studies that try to discern the influence of disturbance on biogeochemical outputs from catchments. 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 uniform 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 (Kuraś *et al* 2008, Shaman *et al* 2004, e.g. Woods *et al* 1995) . 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 at 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 long-term average runoff metrics (Nicolson 1988, Buttle and Eimers 2009, Gottschalk *et al* 2006, Yanai *et al* 2015). The hydrologic community has recently put forward a large effort in increasing understanding of heterogeneity of 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, model predictions and/or 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.

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 (Basu *et al* 2010, Seibert *et al* 2009), as well as functions 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 variability of Q_{sp} across different spatial and temporal scales using daily streamflow from five years at 14 sites.

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 (64.25° N, 19.80° 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 S1 and Figure S1). 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. Details on the catchments can be found in Table S1 and in *Laudon et al.* (2013). Bedrock type in the Krycklan catchment shows little variation, and is dominated by gneissic metagraywacke and metasediments (94%).

2.2 Streamflow data

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}) is defined as the discharge observed at each monitoring station per unit contributing 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.

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 5 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.

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 5-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 5 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.

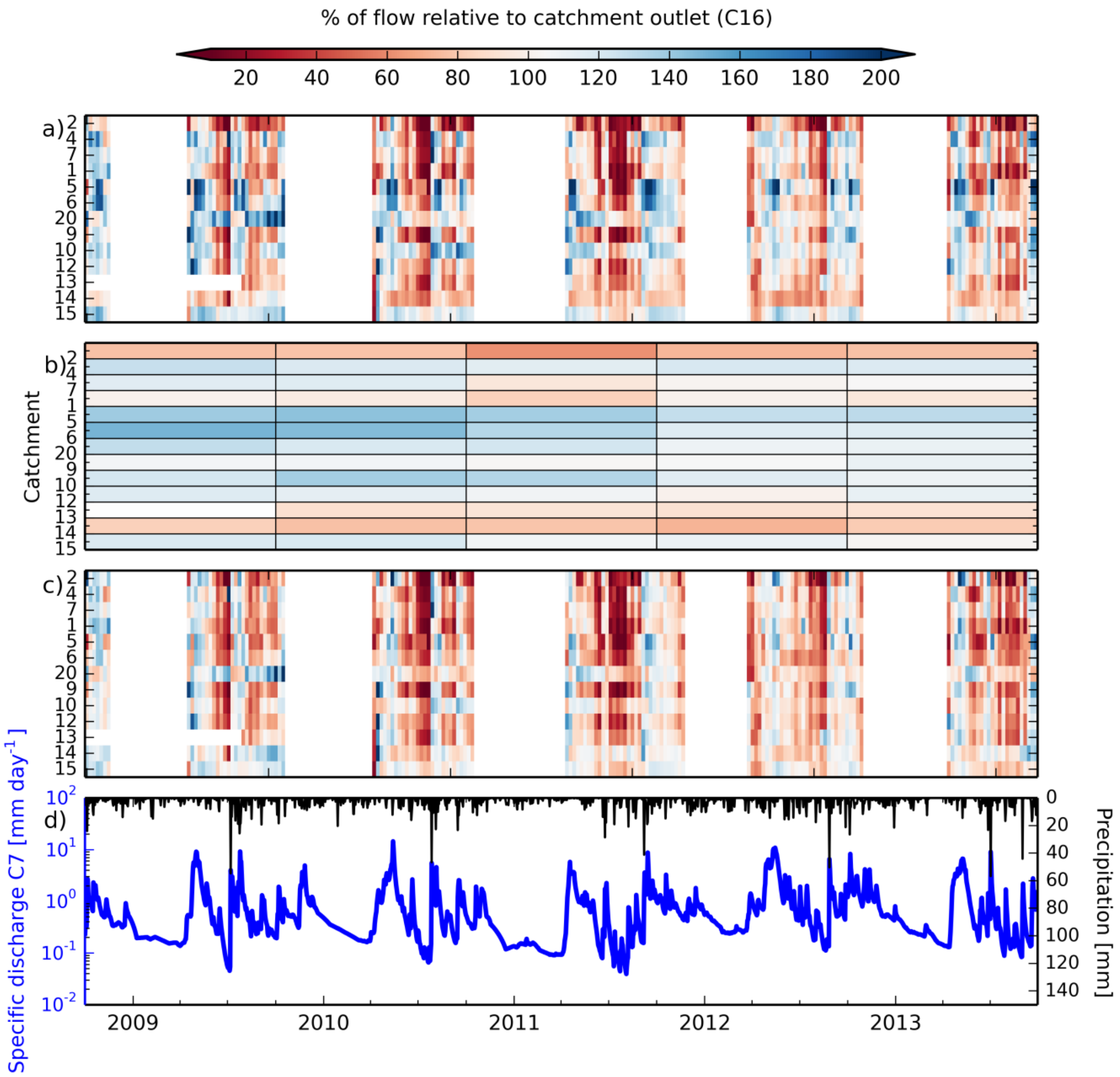

Figure 1 Temporal variability in percentage flow relative to the main outlet (C16) for a) weekly aggregation, b) annual aggregation (hydrological year) and c) weekly aggregation where catchment areas are scaled to yield uniform specific discharge in the 5-year aggregation of catchment flows. Blank periods 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.

For the aggregated 5 year period, the inter-catchment variability in Q_{sp} ranged from 74% to 135% (C_{IQR} 20%) relative to the main outlet (C16). On an annual temporal scale the variation ranged between 61% and 150% (C_{IQR} 19%, Figure 1 and Table S2). Seasonal catchment spatial variability was similar to the annual period. Relative to the catchment outlet, spring water yields vary 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 subcatchments.

The spatial and temporal variability increased considerably when moving from longer to shorter timescales (Figure 1, 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 (Figure 2). The inter-site difference in Q_{sp} can be low during long timescales, such as annual or quarterly, but increases when considering shorter timescales. Rainfall events, in the example of Figure 2, 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 S2).

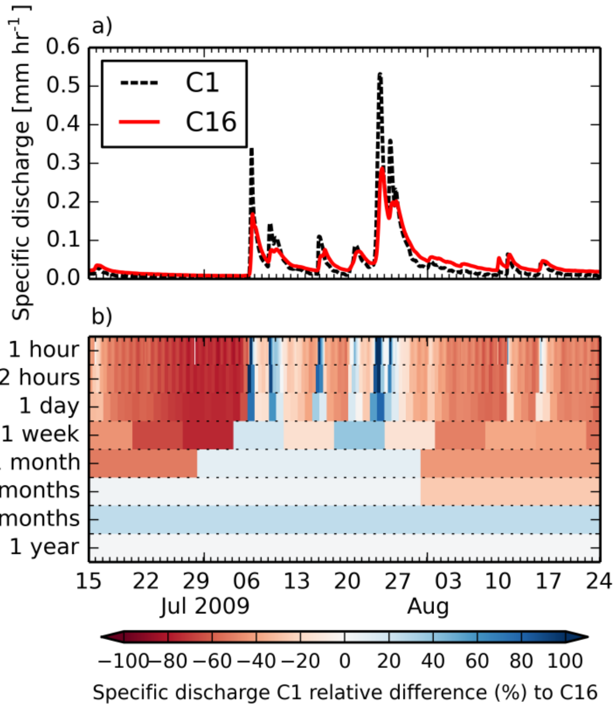

Figure 2 Temporal variability in the deviation between C1 and C16 during the summer of 2009. On shorter timescales the deviation is strong, while on longer timescales it gradually evens out. These two sites have similar long term specific discharge.

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 S3) 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 flows 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 S2 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.

Flow levels influenced the spatial variability. The coefficient of variation (C_V) between sites for weekly aggregated flows below 1 mm day^{-1} varied between 40-90%, mostly occurring during the summer (Figure 3a). 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% with increasing flow. At these higher flow levels the C_V approaches the spatial C_V observed for annual Q_{sp} (14-21%). 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 3b) was higher for the smaller subcatchments across timescales from daily to several months (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 longer timescales, and on the annual scale the SD_{log} varied between 0.15 and 0.3 with no clear relation to catchment area.

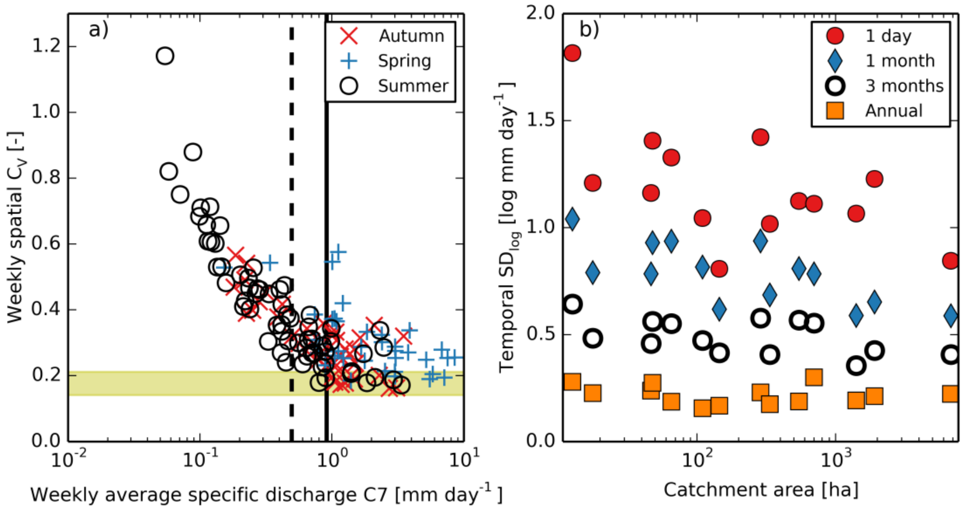

Figure 3 a) Spatial coefficient of variation (C_V) and standard deviation of weekly aggregated flow for different flow levels. High values during spring falling above the point cloud were from the beginning of the melting period. Horizontal shaded area shows the range of C_V for the different hydrological years. 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 SD_{log} are significant ($p < 0.1$) for daily to quarterly aggregation, while annual variability is not significantly related to catchment area ($p = 0.45$).

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 (e.g. Gardner *et al* 2011, Judd *et al* 2011, Lidman *et al* 2014, Hosseini *et al* 2012, Emerson *et al* 2005, Farmer and Vogel 2013, Archfield and Vogel 2010).

A large spatial variability in Q_{sp} was observed between nearby sub-catchments within the Krycklan watershed (Figure 1 and Table S2), showing considerable deviations from previously assumed uniform spatial 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). 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 Krycklan in this study on 14 sites is 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 having high flow during summer (i.e. the ranking of catchment flow magnitudes change between summer and spring). When comparing the Q_{sp} during the summer with the strength of the correlation with spring periods, it is the relatively wet summers that show stronger spatial consistency with spring flow, while the drier summers show weaker spatial consistency. This indicates that there is 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 dependency of hydrological and biogeochemical processes (e.g. Ågren *et al* 2007, Payn *et al* 2012).

The between site variability showed a larger range at shorter temporal scales, e.g. the 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 flow magnitudes (Figure 3), displaying a strong increase in variability at flow levels below 1 mm day^{-1}. At higher flow rates the relative variability, even at shorter timescales, approaches 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, is 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 3b). 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).

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} in smaller catchments, we argue that it is particularly important to measure and understand the variability observed at smaller scales, since ignorance can confound interpretations of hydrological and biogeochemical processes within the landscape.

4.1 Sources of error

Errors are present in all measurements, and three main error sources could be contributing to variability in Q_{sp}: rating curve definition, areal precipitation and catchment area. Catchment area will give persistent, systematic errors which would be reflected most clearly in the cumulative 5 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 S4). The weekly relative difference of the scaled time series (Figure 1 panel c) shows little difference in the ranges of variability compared to the measured, unscaled time-series (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.

Rating curve uncertainties resulted in calculated flow uncertainties ranging from 3 to 11%, with an average for all catchments of 6% (c.f. text S3). Given the well-defined rating curves and frequent streamflow gauging performed over the range of flow extremes observed, we conclude that these errors are too small to result in the large variability and patterns that we observe. We also 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).

Five precipitation gauges outside the catchment operated by the Swedish Meteorological and Hydrological Institute show very 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 S5). However, at the shorter term (e.g. daily to monthly) precipitation shows larger variation in space, but without structure (Figure S3). 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 been reported from synoptic campaigns (Lyon *et al* 2012). Given that uncertainties are not the main source for much of the observed variability in Q_{sp}, we reject the assumption that Q_{sp} can be considered uniform across landscapes until there is an even greater degree of uniformity than that found in the Krycklan basin.

The observed variabilities are on the same order of magnitude as predicted change 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 and Seibert 2012). 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 land-use and climate change. The high 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, all mean summer volumetric flow rates are correlated to catchment area with $r^2 > 0.99$ 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 at shorter timescales, we hypothesize that the spatial variability in precipitation can also result in random variability in Q_{sp}. The subsequent streamflow recession can result in differences over several weeks to months. For longer than seasonal timescales, much of the discharge variability evens out and remains more constant over time (Figure 1 and Figure 2). The structured variability within different timescales is hypothesized to be caused primarily by the spatial differences in landscape factors such as soils, vegetation and topography. This variability can, for instance, originate in different flow pathways, storages and flow rates through the soils, which in turn have a large influence on the water quality and landscape connectivity of these streams (Seibert *et al* 2009, Ågren *et al* 2014). For example, during different storage conditions the variability in which parts of the landscape are connected and contributing to streamflow can be large (Jencso and McGlynn 2011).

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 also a source of information from which we can seek further understanding of the landscape structure in hydrological response and catchment functioning. 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 (Sivapalan 2005, McDonnell and Woods 2004).

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References

Ågren A, Buffam I, Jansson M and Laudon H 2007 Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export *J. Geophys. Res.* **112** G03003

Ågren A M, Buffam I, Cooper D M, Tiwari T, Evans C D and Laudon H 2014 Can the heterogeneity in stream dissolved organic carbon be explained by contributing landscape elements? *Biogeosciences* **11** 1199–213

Andréasson J, Bergström S, Carlsson B, Graham L P and Lindström G 2004 Hydrological change--climate change impact simulations for Sweden. *Ambio* **33** 228–34

Archfield S A and Vogel R M 2010 Map correlation method: Selection of a reference streamgage to estimate daily streamflow at ungaged catchments *Water Resour. Res.* **46** W10513

Asano Y and Uchida T 2010 Is representative elementary area defined by a simple mixing of variable small streams in headwater catchments? *Hydrol. Process.* **24** 666–71

Basu N B, Destouni G, Jawitz J W, Thompson S E, Loukinova N V., Darracq A, Zanardo S, Yaeger M, Sivapalan M, Rinaldo A and Rao P S C 2010 Nutrient loads exported from managed catchments reveal emergent biogeochemical stationarity *Geophys. Res. Lett.* **37** 1–5

Bergström S 1976 *Development and application of a conceptual runoff model for Scandinavian catchments* (Norrköping, Sweden: SMHI Reports RHO, No. 7)

Bishop K H, Buffam I, Erlandsson M, Fölster J, Laudon H, Seibert J and Temnerud J 2008 Aqua Incognita: the unknown headwaters *Hydrol. Process.* **22** 1239–42

Buttle J M and Eimers M C 2009 Scaling and physiographic controls on streamflow behaviour on the Precambrian Shield, south-central Ontario *J. Hydrol.* **374** 360–72

Darracq A and Destouni G 2005 In-Stream Nitrogen Attenuation: Model-Aggregation Effects and Implications for Coastal Nitrogen Impacts *Environ. Sci. Technol.* **39** 3716–22

Emerson D G, Vecchia A V and Dahl A L 2005 *Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for the Red River of the North Basin , North Dakota and Minnesota* (USGS, Scientific Investigations Report 2005–5017)

Farmer W H and Vogel R M 2013 Performance-weighted methods for estimating monthly streamflow at ungauged sites *J. Hydrol.* **477** 240–50

Gardner K K, Mcglynn B L and Marshall L A 2011 Quantifying watershed sensitivity to spatially variable N loading and the relative importance of watershed N retention mechanisms *Water Resour. Res.* **47** 1–21

Gottschalk L, Krasovskaia I, Leblois E and Sauquet E 2006 Mapping mean and variance of runoff in a river basin *Hydrol. Earth Syst. Sci. Discuss.* **3** 299–333

Grayson R B, Western A W, Chiew F H S and Blöschl G 1997 Preferred states in spatial soil moisture patterns: Local and nonlocal controls *Water Resour. Res.* **33** 2897–908

Hosseini N A A, Parker W J J and Matott L S L 2012 Modelling Concentrations of Pharmaceuticals and Personal Care Products in a Canadian Watershed *Can. Water Resour. J.* **37** 191–208

Hrachowitz M, Savenije H H G, Blöschl G, McDonnell J J, Sivapalan M, Pomeroy J W, Arheimer B, Blume T, Clark M P, Ehret U, Fenicia F, Freer J E, Gelfan a., Gupta H V, Hughes D a., Hut R W, Montanari a., Pande S, Tetzlaff D, Troch P a., Uhlenbrook S, Wagener T, Winsemius H C, Woods R a., Zehe E and Cudennec C 2013 A decade of Predictions in Ungauged Basins (PUB)—a review *Hydrol. Sci. J.* **58** 1198–255

Ide J, Finér L, Laurén A, Piirainen S and Launiainen S 2013 Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland *For. Ecol. Manage.* **304** 482–91

Jencso K G and McGlynn B L 2011 Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation *Water Resour. Res.* **47** W11527

Jónsdóttir J F, Uvo C B and Clarke R T 2008 Filling Gaps in Measured Discharge Series with Model-Generated Series *J. Hydrol. Eng.* **13** 905–9

Judd K E, Likens G E, Buso D C and Bailey A S 2011 Minimal response in watershed nitrate export to severe soil frost raises questions about nutrient dynamics in the Hubbard Brook experimental forest *Biogeochemistry* **106** 443–59

Kumar P 2007 Variability, Feedback, and Cooperative Process Dynamics: Elements of a Unifying Hydrologic Theory *Geogr. Compass* **1** 1338–60

Kuraś P K, Weiler M and Alila Y 2008 The spatiotemporal variability of runoff generation and groundwater dynamics in a snow-dominated catchment *J. Hydrol.* **352** 50–66

Laudon H, Berggren M, Ågren A, Buffam I, Bishop K H, Grabs T, Jansson M and Köhler S 2011 Patterns and Dynamics of Dissolved Organic Carbon (DOC) in Boreal Streams: The Role of Processes, Connectivity, and Scaling *Ecosystems* **14** 880–93

Laudon H, Taberman I, Ågren A, Futter M, Ottosson-Löfvenius M and Bishop K 2013 The Krycklan Catchment Study-A flagship infrastructure for hydrology, biogeochemistry, and climate research in the boreal landscape *Water Resour. Res.* **49** 7154–8

Lidman F, Köhler S J, Mörth C M and Laudon H 2014 Metal transport in the boreal landscape-the role of wetlands and the affinity for organic matter *Environ. Sci. Technol.* **48** 3783–90

Lindsay J B and Evans M G 2008 The influence of elevation error on the morphometrics of channel networks extracted from DEMs and the implications for hydrological modelling *Hydrol. Process.* **22** 1588–603

Lyon S W, Nathanson M, Spans A, Grabs T, Laudon H, Temnerud J, Bishop K H and Seibert J 2012 Specific discharge variability in a boreal landscape *Water Resour. Res.* **48** W08506

McClain M E, Boyer E W, Dent C L, Gergel S E, Grimm N B, Groffman P M, Hart S C, Harvey J W, Johnston C a., Mayorga E, McDowell W H and Pinay G 2003 Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems *Ecosystems* **6** 301–12

McDonnell J J, Sivapalan M, Vaché K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick M L, Selker J and Weiler M 2007 Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology *Water Resour. Res.* **43** W07301

McDonnell J J and Woods R 2004 On the need for catchment classification *J. Hydrol.* **299** 2–3

Nicolson J A 1988 Water and Chemical Budgets for Terrestrial Basins at the Turkey Lakes Watershed *Can. J. Fish. Aquat. Sci.* **45** s88–95

O'Callaghan J F and Mark D M 1984 The extraction of drainage networks from digital elevation data *Comput. Vision, Graph. Image Process.* **27** 247

Payn R A, Gooseff M N, McGlynn B L, Bencala K E and Wondzell S M 2012 Exploring changes in the spatial distribution of stream baseflow generation during a seasonal recession *Water Resour. Res.* **48** 1–15

Seibert J, Grabs T, Köhler S, Laudon H, Winterdahl M and Bishop K H 2009 Linking soil- and stream-water chemistry based on a Riparian Flow-Concentration Integration Model *Hydrol. Earth Syst. Sci.* **13** 2287–97

Seibert J and Vis M J P 2012 Teaching hydrological modeling with a user-friendly catchment-runoff-model software package *Hydrol. Earth Syst. Sci.* **16** 3315–25

Shaman J, Stieglitz M and Burns D 2004 Are big basins just the sum of small catchments? *Hydrol. Process.* **18** 3195–206

Sivapalan M 2005 Pattern, process and function: Elements of a unified theory of hydrology at the catchment scale *Encyclopedia of Hydrological Sciences* ed M G Anderson and J J McDonnell (John Wiley & Sons, Ltd, New York) pp 193–219

Sørensen R, Ring E, Meili M, Högbom L, Seibert J, Grabs T, Laudon H and Bishop K H 2009 Forest Harvest Increases Runoff Most during Low Flows in Two Boreal Streams *AMBIO A J. Hum. Environ.* **38** 357–63

Soulsby C, Tetzlaff D, Dunn S M and Waldron S 2006 Scaling up and out in runoff process understanding: insights from nested experimental catchment studies *Hydrol. Process.* **20** 2461–5

Spearman C 1904 The proof and measurement of association between two things *Am. J. Psychol.* **15** 72–101

Temnerud J, Seibert J, Jansson M and Bishop K H 2007 Spatial variation in discharge and concentrations of organic carbon in a catchment network of boreal streams in northern Sweden *J. Hydrol.* **342** 72–87

Tetzlaff D, Soulsby C, Youngson A F, Gibbins C, Bacon P J, Malcolm I A and Langan S 2005 Variability in stream discharge and temperature: a preliminary assessment of the implications for juvenile and spawning Atlantic salmon *Hydrol. Earth Syst. Sci.* **9** 193–208

Teutschbein C and Seibert J 2012 Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods *J. Hydrol.* **456-457** 12–29

Vedin H 1995 Lufttemperatur, årstiderna *Sveriges nationalatlas: Klimat, sjöar och vattendrag* (Stockholm) p 176

Wagener T, Sivapalan M, Troch P and Woods R 2007 Catchment Classification and Hydrologic Similarity *Geogr. Compass* **1** 901–31

Woods R 2005 Hydrologic Concepts of Variability and Scale *Encycl. Hydrol. Sci.* 23–40

Woods R, Sivapalan M and Duncan M 1995 Investigating the representative elementary area concept: An approach based on field data *Hydrol. Process.* **9** 291–312

Wrede S, Seibert J and Uhlenbrook S 2013 Distributed conceptual modelling in a Swedish lowland catchment: a multi-criteria model assessment *Hydrol. Res.* **44** 318–33

Yanai R D, Tokuchi N, Campbell J L, Green M B, Matsuzaki E, Laseter S N, Brown C L, Bailey A S, Lyons P, Levine C R, Buso D C, Likens G E, Knoepp J D and Fukushima K 2015 Sources of uncertainty in estimating stream solute export from headwater catchments at three sites *Hydrol. Process.* **29** 1793–805