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Catchments on the cusp? Structural and functional change in northern ecohydrology

D. Tetzlaff,[1]* C. Soulsby,[1] J. Buttle,[2] R. Capell,[1] S. K. Carey,[3] H. Laudon,[4] J. McDonnell,[5,1] K. McGuire,[6] J. Seibert[7,8] and J. Shanley[8]

[1] *Northern Rivers Institute, School of Geosciences, University of Aberdeen, Scotland, UK*
[2] *Department of Geography, Trent University, Ontario, Canada*
[3] *School of Geography and Earth Sciences, McMaster University, Ontario, Canada*
[4] *Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden*
[5] *Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, Saskatchewan, Canada*
[6] *Virginia Water Resources Research Center and Department of Forest Resources and Environmental Conservation, Virginia Tech, VA, USA*
[7] *Department of Geography, University of Zurich, Zurich, Switzerland*
[8] *U.S. Geological Survey, Montpelier, VT, USA*

*Correspondence to: Doerthe Tetzlaff, Northern Rivers Institute, School of Geosciences, University of Aberdeen, Scotland, UK. E-mail: d.tetzlaff@abdn.ac.uk

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Introduction

There is already compelling evidence that climate change in northern temperate, boreal and sub-arctic catchments is having a major effect on hydrological processes (McClelland *et al*., 2006; Rennermalm *et al*., 2010). The Commentary considers the cascade of implications of changes in the annual water balance and seasonal streamflow distribution that can be anticipated for water quality and in-stream ecology in northern regions. Critical uncertainties, urgent research needs and sensitivities in the water balance are identified, highlighting that many of these catchments are 'on the cusp' of major change. In particular, uncertainties over the key role of natural or managed changes in catchment vegetation in mediating the impacts on the water quantity, quality and ecology of river systems will be emphasized. Addressing this research gap will be critical in providing support for adaptive land management aimed at protecting water resources and sustaining ecosystem services. The focus for the discussion are nine catchments (see Carey *et al*., 2010 for details) included in the North-Watch (www.abdn.ac.uk/northwatch) project, an international network of experimental catchments for comparative hydrological study, which span a range of hydroclimatic conditions in the mid-latitude to high-latitude region (e.g. Carey *et al*., 2010). The availability of hydrochemical and ecological data at most of these catchments facilitated synthesis in hypothesizing the integrated projections of climatic warming. Figure 1 shows the projected climate changes between present and the mid-21st century for these nine sites. Although predicted changes in precipitation totals are small at most sites, temperature increases will be marked as General Circulation Model (GCMs) project some of the most dramatic global temperature increases for this region (Intergovernmental Panel on Climate Change, IPCC, 2007; Kundzewicz *et al*., 2007).

Changing Hydrology in Northern Catchments

Changes in magnitude, timing and phase of precipitation, along with changing temperatures, will affect hydrological processes, water balance and short-term hydrological dynamics via melt rates, as well as flow path partitioning at the North-Watch sites (e.g. Capell *et al*., 2013b) and throughout the broader North (Kundzewicz *et al*., 2007). The way in which climatic forcing changes the hydrological function of catchments will be mediated by their structure, i.e. the characteristics and spatial arrangements of geology, topography, soils and vegetation communities (Ali *et al*., 2012). In the short term, vegetation will be the most responsive element of structure, and this will, in turn, interface with changes to hydrological function such as the storage, mixing and release of water (Donohue *et al*., 2007). Vegetation communities will respond to rising temperatures and an increasing proportion of precipitation falling as rain. For example, their composition and distribution can be expected to change, and also the physiology of species may adjust, reflecting prolonged evolutionary

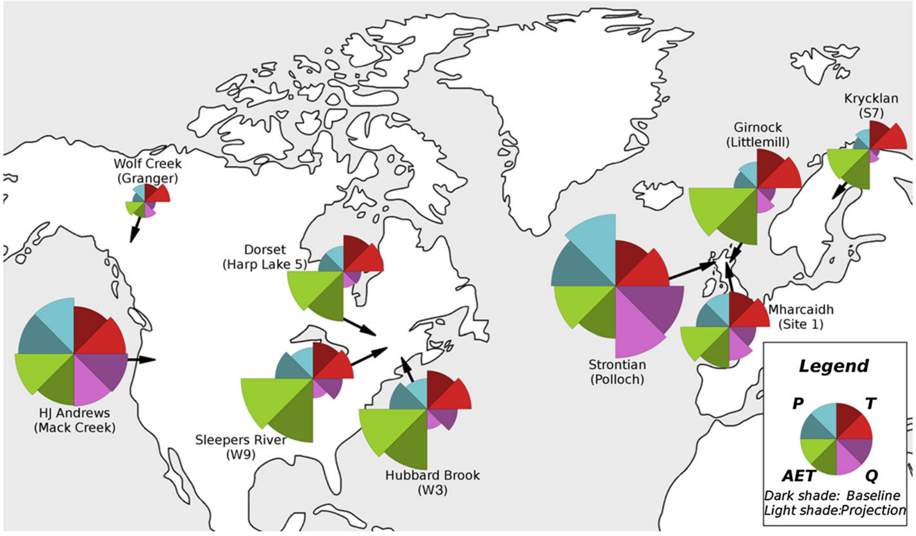

Figure 1. Comparison of annual air temperature and water balance variables across the North-Watch sites as pie charts showing current and mid-21st Century projections based on the Intergovernmental Panel on Climate Change assessment. Segment sizes of precipitation, evapotranspiration and runoff are scaled individually, allowing intercatchment comparison of each variable (segment sizes not to scale for within-catchment water balances)

adaptation to climatic variability through past glacial and interglacial periods (Wookey *et al*., 2009). The ways in which existing dominant species can adapt to changing hydroclimatic regimes, through altered rooting patterns, growth rates, leaf phenology and stomatal control on water losses, will play a key role in determining how the hydrology of catchments will be affected. This will determine both the overall water balance and the short-term hydrological dynamics via melt rates, as well as flow path partitioning (e.g. Brooks *et al*., 2010). Furthermore, vegetation structure provides feedbacks that influence patterns of snow accumulation, re-distribution and melt in northern catchments (Pomeroy *et al*., 2006; Bewley *et al*., 2010; Essery and Pomeroy, 2010).

Classification of northern catchments has potential in providing a systematic basis for conceptualizing how such future changes in hydrology may occur in different regions (Wagener *et al*., 2007). Unfortunately, the issue of classification in hydrology is challenging, and there is little agreement on how best it is approached in a consistent manner (Ali *et al*., 2012). In contrast, general classifications in ecology can provide a framework that acts as a useful starting point. For example, vegetation characteristics of the major biomes can be generally classified simply on the basis of mean annual precipitation and temperatures (Shuttleworth, 1983). The North-Watch catchments span a hydroclimatic gradient from the Scottish Highlands through the Canadian sub-arctic (Carey *et al*., 2010). The combination of mean annual precipitation and mean annual temperature result in vegetation communities that range through different major biomes from tundra (Wolf Creek, Canada) through coniferous boreal forest (Krycklan in Sweden and Mharcaid in Scotland) to mixed broadleaved/coniferous forests (Dorset, Hubbard Brook and Sleepers River in North America or the Girnock in Scotland) and temperate rainforest (at Strontian in Scotland and HJ Andrews in the US) (Figure 2). The climate change projections shown in Figure 1 indicate that some sites could be highly susceptible to change because they are

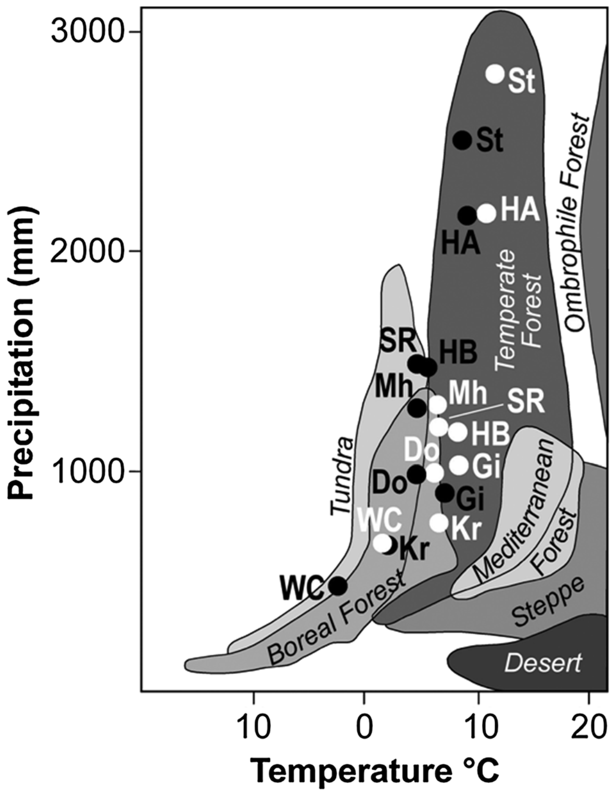

Figure 2. Interrelationships between hdyroclimate (mean annual precipitation and mean annual temperatures) and major biomes showing locations of the North-Watch sites at present (black dots) and future scenarios (white dots) (after Shuttleworth, 1983)

close to the boundary or on the cusp between biome types (Figure 2), although we acknowledge that these boundaries drawn between the classes are artificial and that different classification systems may appear to be more or less sensitive. Hydroclimatic change predicted from GCMs indicates that impacts are likely to be greatest at sites further north (Intergovernmental Panel on Climate Change, IPCC, 2007). For example, Wolf Creek may move from Tundra to Boreal forest as temperatures increase and permafrost thaws. Indeed, there is evidence that this is already happening (Hinzman *et al.*, 2005); warming temperatures affect the disposition of the forest, largely through the expansion of shrubs and the upward migration of treeline (Danby and Hik, 2007) (Figure 2). Likewise, more boreal sites such as Krycklan and the Mharcaidh are on trajectories towards more mixed northern forests with increased expansion of broadleaved tree cover relative to conifers as temperatures increase. Although the details of change at any particular site will be more complex and modulated by subtleties of topography, soils and aspect (Christensen *et al.*, 2008), major vegetation responses over the coming decades are likely, although the longevity of forest communities means it may take a long time for the responses to become apparent (e.g. changes manifested through soil development). That said, unexpected changes are also possible, for example, increased fire influence or heat stress in areas where increased summer aridity may occur (Allen *et al.*, 2010).

Dynamics of Change in Water Balance – the Unknown Role of Vegetation

An enduring model for differentiating the hydrological characteristics of catchments is the Budyko (1974) curve, which plots the ratio of mean annual actual evaporation (E) to mean annual precipitation (P) as a function of an aridity index given by the mean annual potential evaporation (Ep – as a proxy for net radiant energy) to P. This shows that climate (as conceptualized by Ep/P) is a reasonable first-order predictor of annual water balance, which can be a tool to aid hydrological classification (Jones *et al.*, 2012). Plotting the North-Watch catchments by using the Budyko model for 10 years averaged data differentiates the catchments according to climate (Figure 3). This separates out the wetter catchments of HJ Andrews (in north-western USA) and Strontian (in the western Scottish Highlands) from the drier catchments of Krycklan in eastern Sweden and Girnock in eastern Scotland. However, the driest catchment of Wolf Creek also plots in the lower left of the figure as a result of the low energy available for evaporation.

A criticism of approaches such as that of Budyko has been the assumption of stationarity in hydroclimatic conditions (cf. Milly *et al.*, 2008). However, this does not preclude its use as a tool to assess future change (Jones

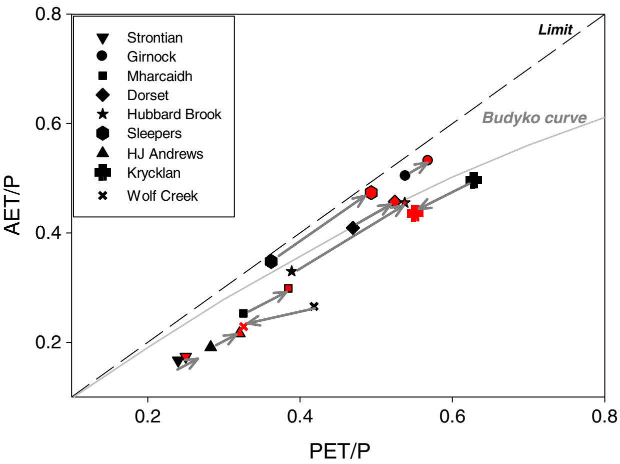

Figure 3. The Budyko model for 10 years averaged data for the North-Watch sites. Black symbols show current average conditions, and red symbols show predicted future conditions derived from the Intergovernmental Panel on Climate Change scenarios

et al., 2012). Thus, the locations of the North-Watch sites on the Budyko curve were also plotted using the climate change scenarios indicated in Figure 1, to see how positions are likely to change by the mid-21st century. With the exception of Wolf Creek and Krycklan, all sites appear to be moving to a situation of increasing aridity where the importance of E as a component of the water balance, resulting from increases in Ep, will increase relative to any increase in precipitation. In relative terms, however, the sites are not arid and remain more energy limited than water limited. At Krycklan and Wolf Creek, the increases in E and Ep are offset by projected increases in precipitation. However, a major uncertainty relates to another simplifying assumption of the Budyko curve in that vegetation plays a passive role (Donohue *et al.*, 2007). In reality, changes in temperature and/or precipitation will lead to a response in vegetation and ecohydrological relations. This may involve changes in the physiology of existing species, which may become more efficient at limiting transpiration if water availability is stressed, or vice versa (Jones *et al.*, 2012). However, it may be that the composition and abundance of species will change, and this can subsequently have an effect on both interception losses and subsequent partitioning of effective precipitation as either snow or rain (Stephenson, 1990).

Although the Budyko curve is useful for comparing the water balance of places, its traditional use at the annual scale provides limited insight into the trajectory of sub-annual hydrological conditions. Nevertheless, it is this sub-annual change that is likely to result in the most important consequences of the North-Watch catchments to climate change. A critically important threshold in Northern catchments is the 0 °C value, the frequency with which it is crossed during the year as the energy budget changes, and the length of time temperatures are below it. The frequency the temperature threshold is crossed is highly variable, yet it determines the relative importance of precipitation inputs as snow, the length of snowpack duration and the frequency and rate of melt (Kundzewicz *et al.*, 2012). This, in turn, has a key influence at the site scale on hydrologic processes such as soil freezing and thawing and the consequent implications for soil infiltrability (e.g. Hardy *et al.*, 2001; Zhang *et al.*, 2010), and at the basin scale on rainfall–runoff relationships as well as the intra-annual and interannual variability of the flow regime (e.g. Goode *et al.*, 2013; Campbell *et al.*, 2011; Spence *et al.*, 2011).

Snowpack development and melt dynamics vary among the North-Watch catchments, resulting in strongly contrasting snowmelt influences on rainfall–runoff relationships. This is shown in Figure 4, which plots the normalized 10-year coefficient of variation of daily flows (over different averaging periods) for four of the sites. In the more northerly sites such as Wolf Creek, the highest and most variable flows of the year are usually during the spring melt, with invariant flows for a prolonged winter period. This is also the case at Krycklan, although summer or autumn rain events provide high flow variability and the low flow winter period is shorter. At Hubbard Brook, spring melt is predictable in generating high flows, but rainfall-induced high variability is evident during the winter. At Strontian, snow is of minor importance, and rainfall events produce periods of high flow variability throughout the year.

Climate change scenarios for these sites project a lessening of snowmelt dominance. In many cases this will lead to higher winter flows if more precipitation falls as rain, and declining spring and early summer flows as snowpack accumulation is less and the melt season is more intense (e.g. see analysis of Scottish sites by Capell *et al.*, 2013b; Campbell *et al.*, 2011). The way that catchment vegetation responds to these hydroclimatic changes will influence the feedback to water balance and subsequently flow regime. This will be far reaching, ranging from influences on patterns of snow accumulation, re-distribution and melt, as well as interception and transpiration losses that can particularly affect summer low flow periods (Yates *et al.*, 2000). Of course, natural vegetation community response to hydroclimatic drivers will occur over the scale of centuries, although some will be more ‘fluid’ and rapid depending on the speed of climate change, the species involved and local factors such as soil, topography and aspect, as well as extreme climatic events (e.g. increased

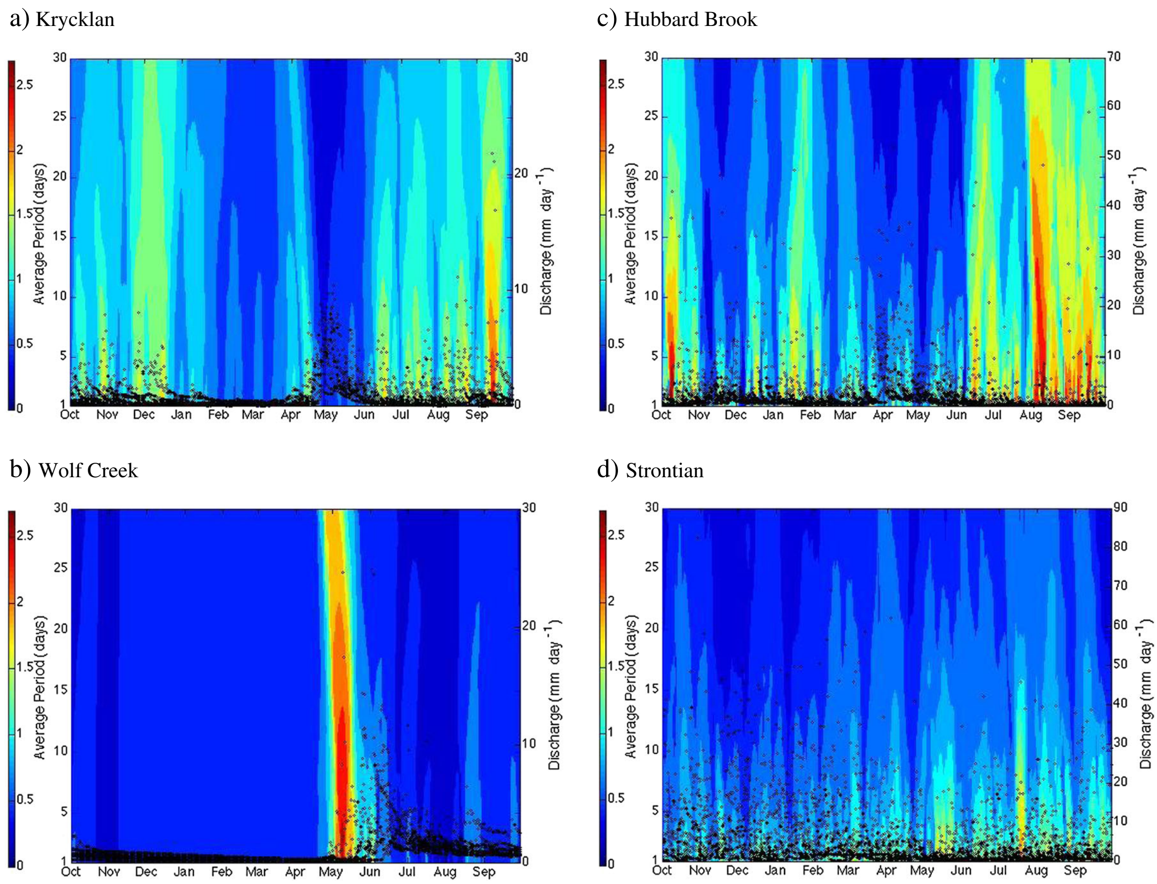

Figure 4. Colour maps of the coefficient of variation of flow. Left *y*-axis is the averaging period, and flows are the black dots (10 calendar years per day) plotted on the right axis. Colour depth grades from blue (low) to red (high) Coefficient of Variation (CV): (a) Krycklan; (b) Wolf Creek; (c) Hubbard Brook; (d) Strontian

frequency of hurricanes projected for north-east America) (Manning *et al*., 2009). However, vegetation is managed in many areas, and land use policy and management responses to mitigate climate change impacts may be of equal importance (e.g. Hrachowitz *et al*., 2010) especially as human population pressure may increase in some localized areas in an ameliorating North (Smith, 2011). Moreover, the ongoing response of vegetation to historic land use change, which may already be affecting vegetation–water relations (e.g. Jones *et al*., 2012), will continue to be important.

Finally, there is the possibility that nonlinearities in the atmospheric response to increasing greenhouse gas emissions may result in sudden and abrupt changes in climatic conditions that might instigate even more rapid vegetation changes (Loarie *et al*., 2009; Beven, 2012). In some places, greater extremes are being experienced, for example, more intense storms, and less evenly distributed precipitation with prolonged drier periods (e.g. Capell *et al*., 2013a). Associated wind damage landslides and droughts may have major implications for vegetation dynamics (e.g. Allen *et al*., 2010). Any vegetation response will overlay the influence of other elements of catchment structure such as geology, topography and soil cover, which will also affect the catchment response at shorter timescale (e.g. Istanbulluoglu *et al*., 2012). This integrated ecohydrological response will determine the degree to which catchment surface and subsurface water storages are able to buffer resistance of the annual streamflow regime to hydroclimatic change (Carey *et al*., in review) as well as the resilience of catchments to recover after periods of extreme events (Carey *et al*., 2010).

Associated Biogeochemical Effects

Such projected changes in hydrology will also have implications for catchment biogeochemistry and stream water quality (Sebestyen *et al*., 2009; Whitehead *et al*., 2009; Pourmokhtarian *et al*., 2012). Dissolved organic carbon (DOC) is a key water quality parameter in northern catchments with organic-rich soils. It has already been shown that DOC production at forested North-Watch sites is strongly related to a combination of moisture availability and temperature (Haei *et al*., 2010; Laudon *et al*., 2011). Intersite variations in terms of the seasonality of DOC concentration and fluxes reflect the interaction of the thermal regime (in terms of winter and summer DOC production) and flow regime (in terms of the timing of catchment export). Currently, the colder sites that have more severe winters (less than $-5\,^{\circ}$C average winter temperatures) experience an annual export concentrated in the spring, whereas sites with warmer winters (>0 °C average winter air temperatures) exhibit more seasonally distributed exports with a winter focus (Laudon *et al*., 2012). As temperatures rise, a likely consequence is that the proportion of annual DOC export in winter will increase along with water fluxes, both for cold sites such as Wolf Creek and Krycklan and more temperate sites such as Sleepers River and Dorset. However, in the longer term, the work of Laudon *et al*. (2013) suggests that the optimum range for DOC production and export in northern catchments are at sites where annual average air temperature lies between 0 and 3 °C (Figure 5). As future temperatures increase, it is hence reasonable to anticipate that DOC concentrations at sites such as Wolf Creek will increase as the large soil organic pool mineralizes, but DOC concentrations at warmer locations will likely decline as the organic pool decreases (Schmidt *et al*., 2011). However, this is another area where the uncertainty regarding the impacts of vegetation response makes prediction difficult as vegetation change will both influence and be influenced by the soil processes that govern DOC production and export. For example, changing quality of soil organic matter can be expected to accompany alterations in vegetation litter, and a shift from coniferous to deciduous vegetation would likely change the labile soil pool and subsequent biochemistry of the DOC components (Dawson *et al*., 2009). The implications for such water quality changes are, of course, much greater than only on DOC, and the reader is referred to Whitehead *et al*. (2009) for a more comprehensive review.

Associated In-stream Ecological Implications

Climatically driven change in streamflow regimes and associated water quality effects will have far reaching

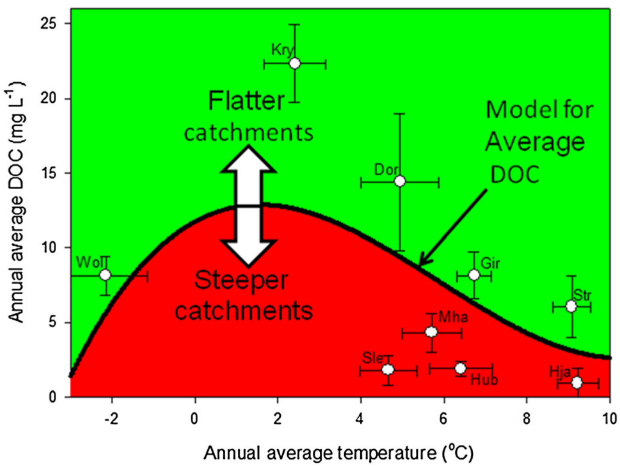

Figure 5. Cross-regional mean annual temperature (MAT)–dissolved organic carbon (DOC) concentration relationship. The regression line model ($DOC = 11.62 + 1.51*MAT - 0.52*MAT^2 + 0.027*MAT^3$) is based on the literature data only (Laudon *et al*., 2012, for details). Whiskers denote the range in MAT and annual average DOC concentrations for each of the regional average values. The North-Watch research catchments data (Wol, Wolf Creek; Kry, Krycklan; Dor, Dorset; Gir, Girnock; Str, Strontian; Sle, Sleepers River; Mha, Mharcaidh; Hub, Hubbard Brook; Hja, HJ Andrews) are annual MAT and average DOC concentration at each site. Here, whiskers denote standard deviation in annual DOC concentration and MAT

implications for the ecology of northern freshwaters. Temperature is a key driver of biological productivity, and the life cycles of many freshwater organisms are selected for seasonal variations in thermal regimes (Friberg *et al.*, 2013). Likewise, the annual flow regime is often a major influence on in-stream ecology (Poff *et al.*, 1997). As an example, Kruitbos *et al.* (2012) showed that the abundance and diversity of stoneflies (*Plecoptera*) for the North-Watch sites was strongly influenced by both the flow regime and the temperatures (Figure 6). These tended to be highest at the warmer North-Watch sites that had more variable flow regimes and thus higher and more frequent spate events than colder snow-dominated catchments that are dominated by the primacy of the spring melt. As stream temperatures increase and flow regimes are more rainfall influenced, then the composition of macroinvertebrate communities will change, with Plecopterans being likely 'winners' as a result. However, within this general pattern, species-level impacts will be more complex.

Impacts on higher-order species can be hypothesized from studies in one of the Scottish North-Watch catchment, the Girnock, where Atlantic salmon (*Salmo salar*) is a key species whose life cycle is closely keyed into variations in the annual streamflow regime. As an anadromous species, salmon spend up to 3 years in the marine environment. This includes their main period of growth, following an initial 2- to 4-year period as juveniles in freshwater. They then return to freshwater to spawn, and the entry of fish into spawning streams is usually triggered by the onset of higher flows during the autumn and winter periods (Tetzlaff *et al.*, 2007, 2008). Eggs spend the colder and high flow winter period at depths up to 30 cm within river gravels. Eggs hatch and juvenile 'fry' emerges into the water column during May, which is typically the driest month in the Scottish Highlands with the lowest streamflows. This is critical

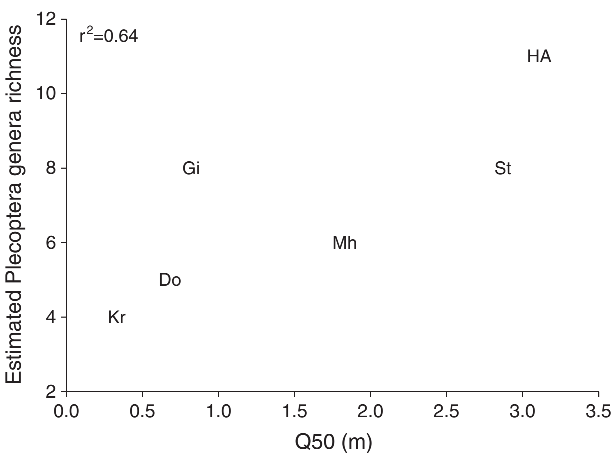

Figure 6. Relationship between *Plecoptera* genera diversity and median annual flow (Q50) for selected North-Watch sites. Kr, Krycklan; Do, Dorset; Gi, Girnock; Mh, Mharcaidh; St, Strontian; HA, HJ Andrews (after Kruitbos *et al.*, 2012)

as these fish have insufficient strength to swim against any current for a few weeks and can suffer catastrophic 'wash-out' during high magnitude–low frequency flows (Tetzlaff *et al.*, 2005a, b). Projected climate changes and likely streamflow effects suggest increased winter high flows and reduced summer low flows for this site (Capell *et al.*, 2013b). This is significant as it may increase the risk of scour of spawning gravels during the winter (cf. Goode *et al.*, 2013) and increase the risk of summer time thermal stress as the thermal capacity at low streamflows is reduced whilst ambient atmospheric temperatures will increase (Cunjak *et al.*, 2013).

Ecohydrology of Northern Vegetation – a Key Research Challenge

The urgent and multifaceted challenges of climate change and associated pronounced transformation in the hydrology of northern catchments highlight the weaknesses of our current science to inform policy for adaptive management. A holistic hydrologic understanding that is more closely integrated with other sciences such as biogeochemistry and freshwater ecology and also social sciences is a prerequisite for more comprehensive predictions of the future (Soulsby *et al.*, 2008). To reach such goals, new approaches need to integrate both small-scale empirical studies to inform modelling studies in both 'top-down' and 'bottom-up' manners (cf. Sivapalan, 2005). Such attempts are not new; indeed, they are truisms to many involved in this research field. Critically, however, long-term study sites, where high quality long-term core data are supplemented by process-based investigations, are fundamental for generating sound data, information and knowledge (Lovett *et al.*, 2007; Burt *et al.*, 2011; Laudon *et al.*, 2011; Jones *et al.*, 2012). This importance of long-term study sites such as those used in North-Watch cannot be overstated at the present time when the economic constraints in many countries are resulting in reduced financial support, or even cessation of monitoring, at sites that are usually funded by public agencies.

Perhaps, the greatest unknown, and a major justification for continued long-term monitoring, is the role of vegetation in modulating the effects of hydrological change. Given increased global population growth and associated development pressures in catchments in localized parts of the hydroclimatic zone captured by the North-Watch catchments, it is probable that the future vegetation response will be more strongly influenced by human decision-making in land use management over larger areas. These decisions – which may result in urban and industrial expansions in some places and increased agriculture and forest harvesting in others – will affect both local energy balances and precipitation partitioning. In many cases, these are likely to produce impacts that are similar to, or greater than, those that are climatically driven. To understand the effect of changes in vegetation, assemblages on hydrological function will require an understanding on how water and energy interact to govern ecosystem function over the lifecycle of vegetation stands. Of course, within individual biomes or even small catchments, different vegetation communities have distinct compositional and functional characteristics that reflect contrasting hydrological process domains. Thus, although some catchments may be more sensitive to change – and closer to the 'cusp' – some parts of catchments will be more sensitive to change than others (Mengistu *et al*., 2013). In some instances, these may be 'hot spots' or very small areas that have a disproportional impact on catchment responses, and it is important that they are recognized by decision makers (McClain *et al*., 2003). In all cases, the needs for evermore carefully integrated land and water management underpinned by evidence-based science is essential. Failure to do so is likely to result in unintended implications that may result in long-term environmental problems (Crouch *et al*., 2013).

Conceptually, such sensitivity of catchments can be thought of in terms of the resistance of the catchment – in terms of streamflow response – to changes in hydroclimatic drivers. Catchment storage of water in the soil and groundwater zones has been recently highlighted as a key internal control on resistance (McNamara *et al*., 2011; Soulsby *et al*., 2011). Similarly, the resilience of catchments – i.e. their ability to recover from major perturbations in terms of hydroclimatic extremes – will also be governed by the physical and ecological characteristics of the catchment (Carey *et al*., 2010). The critical importance of vegetation communities in mediating the hydrological impacts of climate change underlines the need for continued efforts to transfer concepts between hydrology and ecology (e.g. Newman *et al*., 2006). Although some of the structural/functional relationships between water and energy and vegetation communities are understood at larger scales (e.g. Figure 2), the way in which these ecohydrological relations interact in colder snow-influenced regions, even within intensively studied catchments such as those in North-Watch, is not well understood. As discussed previously, the 0 °C value is a critical hydroclimatological threshold in northern catchments; it is also likely to be important for the ecology of vegetation and associated interactions with hydrological processes. Addressing the issues discussed earlier will require using a suite of approaches including remote sensing in upscaling, modeling in refining projections and their associated uncertainties, and comparative, cross-regional synthesis projects such as North-Watch. Experimental catchments with extensive process-based knowledge are crucial integrating activities in such initiatives, so their importance has never been greater.

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References

Ali G, Tetzlaff D, Soulsby C, McDonnell JJ, Capell R. 2012. A comparison of similarity indices for catchment classification using a cross-regional dataset. *Advances in Water Resources* 40: 11–22.

Allen CD, *et al*. 2010. A global overview of drought and heat induced mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259: 660–684.

Beven KJ. 2012. Rainfall-Runoff Modelling: The Primer (2nd Edn) Wiley.

Bewley D, Essery R, Pomeroy J, Menard C. 2010. Measurements and modelling of snowmelt and turbulent heat fluxes over shrub tundra. *Hydrology And Earth System Sciences* 14: 1331–1340.

Brooks R, Barnard H, Coulombe R, McDonnell JJ. 2010. Two water worlds paradox: trees and streams return different water pools to the hydrosphere. *Nature Geoscience* 3: 100–104. DOI: 10.1038/NGEO722

Budyko MI. 1974. Climate and Life. Academic Press.

Burt TP, Howden NJK, Worrall F, McDonnell JJ. 2011. On the value of long-term, low-frequency water quality sampling: avoiding throwing the baby out with the bathwater. *Hydrological Processes* 25(5): 828–830.

Campbell JL, Driscoll CT, Pourmokhtarian A, Hayhoe K. 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. *Water Resour Res.* 47(2): W02514.

Capell R, Tetzlaff D, Essery R, Soulsby C. 2013a. Projecting climate change impacts on stream flow regimes with tracer-aided runoff models – preliminary assessment of heterogeneity at the mesoscale. *Hydrological Processes*. DOI: 10.1002/hyp.9612

Capell R, Tetzlaff D, Soulsby C. 2013b. Will catchment characteristics moderate the projected effects of climate change on flow regimes in the Scottish Highlands. *Hydrological Processes* 27: 687–699. DOI: 10.1002/hyp.9626

Carey SK, Tetzlaff D, Seibert J, Soulsby C, Buttle J, Laudon H, McDonnell J, McGuire K, Caissie D, Shanley J, Kennedy M, Devito K, Pomeroy JW. 2010. Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience. *Hydrological Processes* 24: 3591–3602.

Carey SK, Tetzlaff D, Buttle J, Laudon H, McDonnell J, McGuire K, Seibert J, Soulsby C, Shanley J. Use of colormaps and wavelet coherence to discern short and longer-term climate influences on streamflow variability in northern catchments. *Water Resources Research*. In review.

Christensen L, Christina L, Tague CL, Baron JS. 2008. Spatial patterns of simulated transpiration response to climate variability in a snow dominated mountain ecosystem. *Hydrological Processes* 22: 3576–3588.

Crouch CM, McKnight DM, Todd A. 2013. Quantifying sources of increasing zinc from acid rock drainage in an alpine catchment under a changing hydrologic regime. *Hydrological Processes* 27: 721–733. DOI: 10.1002/hyp.9650

Cunjak R, Linnansaari T, Caissie D. 2013. The complex interaction of ecology and hydrology in a small catchment: a salmon's perspective. *Hydrological Processes* 27: 741–749. DOI: 10.1002/hyp.9640

Danby RK, Hik DS. 2007. Evidence if recent treeline dynamics in southwest Yukon from aerial photographs. *Arctic* 60: 411–420.

Dawson JJC, Malcolm IA, Middlemas S, Tetzlaff D, Soulsby C. 2009. Is the composition of dissolved organic carbon changing in upland acidic streams? *Environmental Science & Technology* 43(20): 7748–7753.

Donohue RJ, Roderick ML, McVicar TR. 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System Sciences* 11: 983–995.

Essery R, Pomeroy J. 2004. Vegetation and topographic control of wind-blown snow distributions in distributed and aggregated simulations for an Arctic tundra basin. *J. Hydrometeor* 5: 735–744.

Friberg N, Bergfur J, Rasmussen J, Sandin L. 2013. Changing Northern catchments: is altered hydrology, temperature or both going to shape future stream communities and ecosystem processes? *Hydrological Processes* 27: 734–740. DOI: 10.1002/hyp.9598

Goode JR, Buffington JM, Tonina D, Isaak DJ, Thurow RF, Wenger S, Nagel D, Luce C, Tetzlaff D, Soulsby C. 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes* 27: 750–765. DOI: 10.1012/hyp9728

Haei M, Öquist MG, Buffam I, Ågren A, Blomkvist P, Bishop K, Ottosson Löfvenius M, Laudon H. 2010. Cold winter soils enhance dissolved organic carbon concentrations in soil and stream water. *Geophysical Research Letters* 37: L08501, DOI: 10.1029/2010GL042821

Hardy JP, Groffmann PM, Fitzhugh RD, Henry KS, Welman AT, Demers JD, Fahey TJ, Driscoll CT, Tierney GL, Nolan S. 2001. Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. *Biogeochemistry* 56: 151–174.

Hinzman L, Bettez N, Bolton WR, Chapin III FS, Dyurgerov M, Fastie C, Griffith B, Hollister RD, Hope A, Huntington HP. 2005. Evidence and implications of recent climate change in terrestrial regions of the Arctic. *Climate Change* 72:251–298.

Hrachowitz M, Soulsby C, Imholt C, Malcolm IA, Tetzlaff D. 2010. Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures. *Hydrological Processes* 24: 3374–3391.

Intergovernmental Panel on Climate Change (IPCC). 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Pachauri RK, Reisinger A (eds). IPCC: Geneva, Switzerland, 104.

Istanbulluoglu E, Wang T, Wright OM, Lenters JD. 2012. Interpretation of hydrological trends from a water balance perspective: the role of groundwater storage in the Budyko hypothesis. *Water Resources Research* 48: W00H16.

Jones J, Creed IF, Hatcher KL, Warren RJ, Adams MB, Benson MH, Boose E, Brown WA, Campbell JL, Covich A, Clow DW, Dahm CN, Elder K, Ford CR, Grimm NB, Henshaw DL, Larson KL, Miles ES, Miles KM, Sebestyen SD, Spargo AT, Stone AB, Vose JM, Williams MW. 2012. Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. *BioScience* 62: 390–404. DOI:10.1525/bio.2012.62.4.10

Kruitbos LM, Tetzlaff D, Soulsby C, Buttle J, Carey S, Laudon H, McDonnell J, McGuire K, Seibert Cunjak R, Shanley J. 2012. Hydroclimatic and hydrochemical controls on *Plecoptera* (stonefly) diversity and distribution in northern freshwater ecosystems. *Hydrobiologia*. DOI: 10.1007/s10750-012-1085-1

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z and Shiklomanov IA. 2007. Freshwater resources and their management. In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson (eds). Cambridge University Press: Cambridge, UK, 173–210.

Kundzewicz ZW, Mata LJ, Arnell NW, Doell P, Jimenez B, Miller K, Oki T, Sen Z, Shiklomanov I. 2012. The implications of projected climate change for freshwater resources and their management. *Hydrological Science Journal* 53: 3–10.

Laudon H, Berggren M, Ågren A, Buffam I, Bishop K, Grabs T, Jansson M, Köhler S. 2011. Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes. *Connectivity, and Scaling Ecosystems* 14: 880–893. DOI: 10.1007/s10021-011-9452-8

Laudon H, Buttle J, Carey SK, McDonnel J, McGuire K, Seibert J, Shanley J, Soulsby C, Tetzlaff D. 2012. Cross-regional prediction of long-term trajectory of stream water DOC response to climate change. *Geophysical Research Letters* 39: L18404. DOI: 10.1029/2012GL053033

Laudon H, Tetzlaff D, Soulsby C, Carey S, Seibert J, Buttle J, Shanley J, McDonnell J, McGuire K. 2013. Change in winter climate will affect dissolved organic carbon and water fluxes in mid- to high latitude catchments. *Hydrological Processes* 27: 700–709. DOI: 10.1002/hyp.9686

Loarie SR, Duffy PB, Hamilton H, Asner GP, Field CB, Ackerly DD. 2009. The velocity of climate change. *Nature* 462: 1052–1054.

Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanley JB, Likens GE, and Haeuber R. 2007. Who needs environmental monitoring? *Frontiers in Ecology and the Environment* 5(5): 253–260.

Manning AD, Fischer J, Felton A, Newell B, Steffen W, Lindenmayer DB. 2009. Landscape fluidity - a unifying perspective for understanding and adapting to globalchange. *Jorunal of Biogeography* 36: 193–199.

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, Pinay G. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems* 6: 301–312. DOI: 10.1007/s10021-003-0161-9

McClelland JW, Déry SJ, Peterson BJ, Holmes RM, Wood EF. 2006. A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. *Geophysical Research Letters* 33: L06715, DOI: 10.1029/2006GL025753

McNamara JP, Tetzlaff D, Bishop K, Soulsby C, Seyfried M, Peters N, Hooper R. 2011. Storage as a metric of catchment comparison. *Hydrological Processes* 25: 3364–3371.

Mengistu SG, Creed IF, Kulperger RJ, Christopher G. 2013. Quick Russian nesting dolls effect – using wavelet analysis to reveal non-stationary and nested stationary signals in water yield from catchments on a northern forested landscape. *Hydrological Processes* 27: 669–686. DOI: 10.1002/hyp.9552

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer, RJ. 2008. Stationarity is dead: whither water management? *Science* 319: 573–574. DOI: 10.1126/science.1151915

Newman BD, Wilcox BP, Archer SR. 2006. Ecohydrology of water-limited environments: a scientific vision. *Water Resources Research* 42(6): W06302.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter B, Sparks R, Stromberg J. 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. *BioScience* 47: 769–784.

Pomeroy JW, Bewley DS, Essery RLH, Hedstrom NR, Link T, Granger RJ, Sicart JE, Ellis CR, Janowicz JR. 2006. Shrub tundra snowmelt. *Hydrological Processes* 20: 923–941. DOI: 10.1002/hyp.6124

Pourmokhtarian A, Driscoll CT, Campbell JL, Hayhoe K. 2012. Modeling potential hydrochemical responses to climate change and increasing CO2 at the Hubbard Brook Experimental Forest using a dynamic biogeochemical model (PnET-BGC). *Water Resources Research* 48(7): W07514.

Rennermalm AK, Wood EF, Troy TJ. 2010. Observed changes in pan-arctic cold season minimum monthly river discharge. *Climate Dynamics* 35(6): 923–939. DOI: 10.1088/1748-9326/4/2/024011

Schmidt MW, Torn MS, Abiven S, Dittmar T, *et al*. 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478: 49–56.

Sebestyen SD, Boyer EW, Shanley JB. 2009. Responses of stream nitrate and DOC loadings to hydrological forcing and climate change in an upland forest of the northeastern United States. *Journal of Geophysical Research* 114: G02002. DOI: 10.1029/2008JG000778

Shuttleworth WJ. 1983. Evaporation models in the global water budget. In Variations in the Global Water Budget. 147–171.

Sivapalan M. 2005. Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale. Encyclopedia of Hydrological Sciences, John Wiley & Sons, Ltd.

Smith LC. 2011. The New North – the World in 2050. Profile Books: London.

Soulsby C, Neal C, Laudon H, Burns DA, Merot P, Bonell M, Dunn SM, Tetzlaff D. 2008. Catchment data for process conceptualization: simply not enough? *Hydrological Processes* 22: 2057–2061.

Soulsby C, Piegat KG, Seibert J, Tetzlaff D. 2011. Catchment-scale estimates of flow path partitioning and water storage based on transit time and runoff modelling. *Hydrological Processes* 25: 3960–3976.

Spence C, Kokelj SV, Ehsanzadeh E. 2011. Precipitation trends contribute to streamflow regime shifts in northern Canada, Cold Region Hydrology in a Changing Climate Proceedings of a symposium held during IUGG 2011 at Melbourne, Australia, June, 2011, IAHS Publ. No. 346, 3–8.

Stephenson N. 1990. Climatic control of vegetation distribution: the role of the water balance. *The American Naturalist* 135: 649–670.

Tetzlaff D, Soulsby C, Gibbins CN, Bacon PJ, Youngson AF. 2005a. An approach to assessing hydrological influences on feeding opportunities of juvenile Atlantic salmon (*Salmo salar*): a case study of two contrasting years in a small, nursery stream. *Hydrobiologia* 549: 65–77.

Tetzlaff D, Soulsby C, Youngson AF, Gibbins CN, Bacon PJ, Malcolm IA, Langan SJ. 2005b. Variability in stream discharge and temperature: a preliminary assessment of the implications for juvenile and spawning Atlantic salmon. *Hydrology and Earth Systems Science* 9: 193–208.

Tetzlaff D, Soulsby C, Bacon PJ, Youngson AF, Gibbins CN, Malcolm IA. 2007. Connectivity between landscapes and riverscapes – a unifying theme in integrating hydrology and ecology in catchment science? *Hydrological Processes* 21: 1385–1389.

Tetzlaff D, Gibbins CN, Bacon PJ, Youngson AF, Soulsby C. 2008. Influence of hydrological regimes on the pre-spawning entry of Atlantic salmon (*Salmo salar* L.) into an upland river. *Rivers Research and Application* 24: 528–542.

Wagener T, Sivapalan M, Troch P, Woods R. 2007. Catchment classification and hydrologic similarity. *Geography Compass* DOI: 10.1111/j.1749-8198.2007.00039.x.

Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ. 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 54: 101–123.

Wookey PA, Aerts R, Bardgett RD, Baptist F, Bråthen KA, Cornelissen JHC, Gough L, Hartley IP, Hopkins DW, Lavorel S, Shaver GR. 2009. Ecosystem feedbacks and cascade processes: understanding their role in the responses of arctic and alpine ecosystems to environmental change. *Global Change Biology* 15: 1153–1172.

Yates DN, Kittel TG, Figge CR. 2000. Comparing the correlative Holdridge model to mechanistic biogeographical models for assessing vegetation distribution response to climate change. *Climatic Change* 44: 59–87.

Zhang Y, Carey SK, Quinton WL, Janowicz JR, Flerchinger GN. 2010. Comparison of algorithms and parameterizations for infiltration into organic-covered permafrost soils. *Hydrological and Earth System Science* 14: 729–750. DOI: 10.5194/hess-14-729-2010