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

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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
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 precipita-
tion 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 Mharcraid 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 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)

Figure 2. Interrelationships between hydroclimate (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 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 ecohidrological 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

![Image](https://example.com/image.png)

**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. İstanbulluoglu 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 (>\(-0^\circ C\) 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...
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, 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 catchments, 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 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,
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References


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INVITED COMMENTARY


