

Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience

Sean K. Carey,^{1*}
Doerthe Tetzlaff,²
Jan Seibert,^{3,4}
Chris Soulsby,² Jim Buttle,⁵
Hjalmar Laudon,⁶
Jeff McDonnell,⁷
Kevin McGuire,⁸
Daniel Caissie,⁹
Jamie Shanley,¹⁰
Mike Kennedy,²
Kevin Devito¹¹ and
John W. Pomeroy¹²

¹ Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada

² Northern Rivers Institute, School of Geosciences, University of Aberdeen, Aberdeen, UK

³ Department of Geography, University of Zurich, Zurich, Switzerland

⁴ Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden

⁵ Department of Geography, Trent University, Peterborough, ON, Canada

⁶ Forest Ecology and Management, SLU, Umeå, Sweden

⁷ Department of Forest Engineering, Oregon State University, Corvallis, OR, USA

⁸ Virginia Water Resources Research Centre, Virginia Tech, Blacksburg, VA, USA

⁹ Fisheries and Oceans, Moncton, NB, Canada

¹⁰ US Geological Survey, VT, USA

¹¹ Department of Biology, University of Alberta, Edmonton, AB, Canada

¹² Centre for Hydrology, University of Saskatchewan, Saskatoon, SK, Canada

*Correspondence to:

Sean K. Carey, Department of Geography and Environmental Studies, Carleton University, Canada.
E-mail: sean_carey@carleton.ca

Received 17 March 2010
Accepted 23 August 2010

Abstract

The higher mid-latitudes of the Northern Hemisphere are particularly sensitive to climate change as small differences in temperature determine frozen ground status, precipitation phase, and the magnitude and timing of snow accumulation and melt. An international inter-catchment comparison program, North-Watch, seeks to improve our understanding of the sensitivity of northern catchments to climate change by examining their hydrological and biogeochemical responses. The catchments are located in Sweden (Krycklan), Scotland (Mharcaidh, Girnock and Strontian), the United States (Sleepers River, Hubbard Brook and HJ Andrews) and Canada (Catamaran, Dorset and Wolf Creek). This briefing presents the initial stage of the North-Watch program, which focuses on how these catchments collect, store and release water and identify 'types' of hydro-climatic catchment response. At most sites, a 10-year data of daily precipitation, discharge and temperature were compiled and evaporation and storage were calculated. Inter-annual and seasonal patterns of hydrological processes were assessed via normalized fluxes and standard flow metrics. At the annual-scale, relations between temperature, precipitation and discharge were compared, highlighting the role of seasonality, wetness and snow/frozen ground. The seasonal pattern and synchronicity of fluxes at the monthly scale provided insight into system memory and the role of storage. We identified types of catchments that rapidly translate precipitation into runoff and others that more readily store water for delayed release. Synchronicity and variance of rainfall–runoff patterns were characterized by the coefficient of variation (*cv*) of monthly fluxes and correlation coefficients. Principal component analysis (PCA) revealed clustering among like catchments in terms of functioning, largely controlled by two components that (i) reflect temperature and precipitation gradients and the correlation of monthly precipitation and discharge and (ii) the seasonality of precipitation and storage. By advancing the ecological concepts of resistance and resilience for catchment functioning, results provided a conceptual framework for understanding susceptibility to hydrological change across northern catchments. Copyright © 2010 John Wiley & Sons, Ltd.

Key Words catchment inter-comparison; water balance; northern temperate regions; functional traits; catchment classification

Introduction

Managing the societal consequences of a changing climate and its impact on the hydrological cycle is one of the 21st Century's major challenges to the prosperity and security of the international community. In few places will the changes and challenges be greater than in the higher mid-latitudes of the Northern Hemisphere where the zero-degree isotherm plays a major role in the phase of precipitation and in intermediate storage as snow (Nijssen *et al.*, 2001; McCabe and Wolock, 2010). For example, there has been considerable observational evidence of decreased snow cover over North America during the last 40 years (Brown and Mote, 2009). In this circumpolar transitional climate zone, small differences in temperature determine the status of frozen ground, the state of precipitation and the magnitude and timing of snow accumulation and melt. Our ability to predict the consequences of climate change on the physical, chemical and biological characteristics of water

resources is a formidable challenge. However, through the analysis of high quality datasets from catchments that encompass integrated measurements of climate, hydrology and ecology, and combined with modelling and theoretical advancements, we can begin to understand how these systems will respond to change. To help achieve this goal, a research program titled North-Watch (*Northern Watershed Ecosystem Response to Climate Change*) has been initiated to examine climate, hydrology and ecology data sets from ten experimental catchments spanning different hydro-climatic zones within Sweden, Scotland, Canada and the United States (Tetzlaff and Carey, 2009). North-Watch (www.abdn.ac.uk/northwatch) is a unique collaboration among process-based hydrologists and biogeochemists representing well-established research sites with extensive combined hydro-climatological, hydrochemical and ecological datasets from different northern regions.

The overall goal of North-Watch is to facilitate an inter-catchment comparison study that will synthesize a comprehensive, interdisciplinary and regional understanding of hydro-climatological and hydrochemical interactions and their ecological consequences, and provide a stronger scientific basis for predicting what the effects of a climate change are likely to be. Through examining a range of sites across a climatic transect in a comparative manner, a stronger regional perspective on climatology–hydrology coupling can be gained compared with assessing individual sites alone. By collating data into inter-comparable structures, we seek to identify the predominant controls on catchment processes and to establish a predictive framework for assessing hydrological, biogeochemical and ecological sensitivity to climatic variability and consequently change in northern regions.

The initial stage, which we focus upon in this paper, of the North-Watch inter-comparison has focussed on the hydrological functioning of the catchments. At its most basic level, hydrological catchment function may be defined as the collection, storage and release of water (Black, 1997). While catchment classification has a long-standing tradition in hydrology based on flow characteristics and yields (Haines *et al.*, 1988) and geomorphology (Leopold *et al.*, 1964), recently catchment function has been advocated as a classification measure (McDonnell and Woods, 2004; Devito *et al.*, 2005; Buttle, 2006; Wagener *et al.*, 2007), and it has been argued that related functional traits can be used to capture and subsume process complexity that occurs within catchments (McDonnell *et al.*, 2007). Functional traits may be used to integrate the spatial–temporal landscape and process patterns that arise as a result of the performance of the catchment function (i.e. the collection, storage and release of water). Functional traits are an ecological concept (Adler *et al.*, 2004; Schulz *et al.*, 2006), which assume that instead of analysing

the complex history of plant evolution (which is usually unknown) one can examine the net result (termed the traits), which embodies all of the relevant historical information. It is hypothesized that functional traits can be connected to catchment function, which could lead to the apparent heterogeneity and process complexity collapsing into a coherent and reproducible pattern, resulting in a simpler explanation for a set of observations than is presently available. Examples of functional traits in hydrology are: fill and spill behaviour (Spence, 2006), catchment connectivity (e.g. Lane *et al.*, 2004; Tetzlaff *et al.*, 2007; Detty and McGuire, 2010), transit times (Soulsby *et al.*, 2006; Tetzlaff *et al.*, 2009), seasonality (Jothityangkoon and Sivapalan, 2009; Tetzlaff *et al.*, 2010), drainage efficiency (Tague *et al.*, 2008; Tague and Grant, 2009), memory and synchronicity (Chen and Kumar, 2002; Devito *et al.*, 2005). Here, we define two functional traits of catchments taken from ecology: resistance and resilience (Folke *et al.*, 2004; Potts *et al.*, 2006). From a catchment perspective, resistance measures the degree to which runoff is coupled/synchronized with precipitation. Catchments that can store water over long time periods (months or years) and release water gradually to the stream have a high resistance, whereas catchments that systematically transfer precipitation into discharge have low resistance. The resistance of catchments relates to its drainage efficiency and storage capacity (Tague *et al.*, 2008; Tague and Grant, 2009). Resilience measures the degree to which a catchment can adjust to normal functioning following perturbations from events such as drought or extreme precipitation. It is hypothesized that catchments with high resilience are able to sustain their expected precipitation–discharge relations in the light of changing inputs, whereas catchments with low resilience are sensitive to changes in inputs and exhibit enhanced threshold response behaviour.

Catchment inter-comparison and classification has a long, although somewhat mixed, history (Jones, 2005; Uchida *et al.*, 2006). Kane and Yang (2004) present water-balance data from 39 circumpolar catchments, although the lack of data standardization, accurate measurement and the variable length of record confounded inter-comparison. Most typically, rainfall–runoff relationships and streamflow metrics are compared, and linked to either (i) some form of treatment such as forest harvesting/land use change in a paired catchment sense (Bosch and Hewlett, 1982; Jones, 2000) or (ii) some catchment characteristic and/or geomorphometry that varies geographically (e.g. Tetzlaff *et al.*, 2009a). What the appropriate type of metric is for a comprehensive catchment classification, or whether it is achievable, remains debatable. However, streamflow indices are most commonly used and have undergone considerable scrutiny with regard to their efficacy (Richter *et al.*, 1998;

Clausen and Biggs, 2000; Archer and Newson, 2002; Olden and Poff, 2003).

Jones (2005) lucidly argues the case for continued inter-site comparison of rainfall–runoff data, particularly as most sites have not been evaluated in a comparative framework to address novel questions. There is a dearth of literature directly comparing headwater and mesoscale catchments with continuous data sets. In addition, other water-balance components such as storage and evapotranspiration are rarely considered as a comparative measure. While rainfall–runoff comparison can be criticized for using ‘black-box’ approach, the inclusion of other hydrological and pertinent catchment information such as temperature, seasonality of response and process synchronicity will provide a basis for the assessment of catchment functional traits, and provide a larger contextual framework to assess the sensitivity of catchments to variability and change.

As an initial step within the North-Watch project, the objectives of this scientific briefing are to (i) characterize the hydrological regimes of ten higher mid-latitude sites along a climate gradient, (ii) evaluate the influence of temperature and precipitation on the magnitude and timing of runoff and storage changes in these different geographic regions and (iii) identify the traits of hydrological functioning to assess sensitivities of catchments to climate variability which would allow certain ‘hydro-climatic catchment response types’ to be identified. Most national hydrometric networks with long-term data focus on large catchments, where stream routing plays a confounding role in the evaluation of catchment functioning. This study focuses on well-established meso- and small-scale research catchments with combined hydro-climatic,

hydrochemical and ecological data sets of several years of data record.

The North-Watch Catchments

Ten catchments traversing a hydro-climate gradient and encompassing a range of geological and soil conditions are selected for inter-comparison across the circum-boreal region (Figure 1). One is located in Sweden, and three each in Scotland, Canada and the United States. All catchments have undergone long-term investigation, and extensive literature exists on the hydrology of each basin.

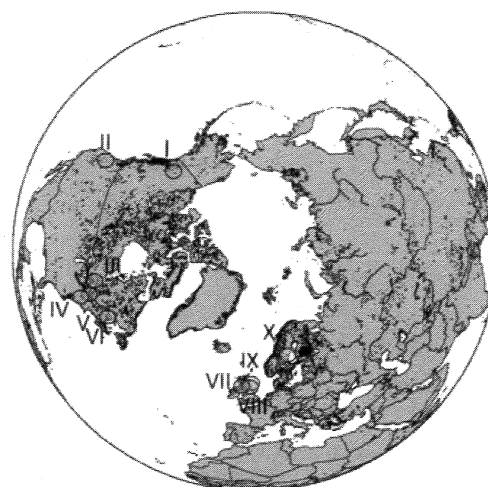


Figure 1. Location of North-Watch catchments: I, Wolf Creek; II, HJ Andrews; III, Dorset; IV, Hubbard Brook; V, Sleepers River; VI, Catamaran; VII, Strontian; VIII, Girnock; IX, Mharcaidh; X, Krycklan

Table I. Site characteristics of the North-Watch study catchments

Country	Catchment	Site	Area (km ²)	Mean altitude (m)	Relief (m)	Dominant geology	Dominant land-use
Scotland	Mharcaidh Girnock	Site 1	10	704	779	Granite	Moorland
		Littlemill	30	405	620	Granite (46)	Moorland/peat (81)
Canada	Strontian	Polloch	8	340	740	Schist, gneiss	Moorland (100)
	Catamaran Brook	Middle Reach	28.7	210	260	Paleozoic volcanic and sedimentary	Secondary growth mixed forest
	Dorset	Harp Lake 5	1.9	373	93	Metamorphic (100)	Forest (87)/peat (13)
	Wolf Creek	Granger Basin	7.6	1700	750	Metasediments	Shrub/subalpine (58) Alpine/tundra (40)
Sweden	Krycklan	S7	0.5	280	72	Metasediments	Forest (85), wetland (15)
USA	HJ Andrews	Mack Creek	5.81	1200	860	Igneous	Forest (100)
	Hubbard Brook	W3	0.41	642	210	Igneous/metamorphic	Northern Hardwood
	Sleepers River	W9	0.41	604	167	Metasediments (100)	Forest (95% deciduous)

Table II. Annual mean climate, runoff, evaporation and storage characteristics for the North-Watch catchments

Catchment	Temperature		Precipitation			Evaporation		Runoff					Storage		Runoff ratio		$cv(Q/P)_A$	$corr(P, Q)_A$
	Mean (°C)	cv	Mean (mm)	cv	% Snow	Mean (mm)	cv	Mean (mm)	cv	Q5 (mm)	Q50 (mm)	Q95 (mm)	Mean (mm)	cv	Mean	cv		
Mharcaidh	5.70	0.07	1222	0.10	20	326	0.05	873	0.12	10.56	1.83	0.39	146	0.42	0.72	0.10	1.19	0.57
Girnock	6.73	0.05	1059	0.10	10	453	0.03	603	0.21	8.96	0.82	0.02	175	0.42	0.57	0.18	2.15	0.61
Strontian	9.08	0.05	2632	0.11	4	417	0.04	2213	0.15	30.08	2.87	0.10	206	0.12	0.84	0.10	1.27	0.69
Catamaran	5.01	0.14	990	0.14	30	453	0.05	534	0.16	10.37	0.87	0.09	242	0.26	0.54	0.09	1.20	0.82
■ Dorset	4.94	0.18	980	0.15	28	401	0.05	577	0.28	11.16	0.70	0.00	263	0.33	0.55	0.26	2.20	0.71
Wolf Creek	−2.15	−0.46	478	0.19	45	127	0.08	352	0.22	4.84	0.49	0.07	141	0.27	0.74	0.16	1.18	0.69
Krycklan	2.41	0.27	651	0.21	40	323	0.05	327	0.40	6.42	0.33	0.00	191	0.25	0.49	0.25	1.90	0.88
HJ Andrews	9.22	0.05	2158	0.25	40	412	0.03	1744	0.29	26.54	3.11	0.29	561	0.36	0.80	0.08	1.16	0.97
Hubbard Brook	6.41	0.10	1381	0.11	25	497	0.03	882	0.18	17.58	0.90	0.01	255	0.30	0.63	0.10	1.70	0.91
Sleepers	4.66	0.19	1256	0.14	25	510	0.06	743	0.23	10.11	1.23	0.01	336	0.23	0.59	0.13	1.65	0.88

$cv(Q/P)_A$ is the ratio of the coefficient of variation of annual runoff and precipitation and $corr(P, Q)_A$ is their annual correlation coefficient for the length of record.

Catchment physical characteristics are summarized in Table I and hydro-climatic characteristics in Table II.

The Krycklan catchments are located on the Fennoscandian shield in Sweden (Buffam *et al.*, 2007). Site S7 (0.5 km²) is used here for intercomparison. Precipitation is ~650 mm, of which 40% falls as snow. Mean annual air temperature is 2.4 °C. The geology is dominated by meta-sediments; soils are mainly podzols. Coniferous forests predominate, although large *Sphagnum*-dominated wetlands cover up to 40% of some of the sub-catchments.

The three Scottish catchments range from 8 to 30 km² in area. Geographically, they include steeper, montane catchments in the maritime northwest (Strontian—which is the wettest of the North-Watch catchments) and the subarctic Cairngorms (Allt a'Mharcaidh) and the lower altitude Girmock in the north-east of Scotland. The mean annual air temperature, which mainly reflects elevation and the degree of continentality, ranges from 5.7 °C for the highest altitude to 9.1 °C for the lowest altitude catchment. Their geology is largely characterized by low permeability igneous and metamorphic rocks (Robins, 1990). At most sites, superficial drifts cover much of the solid geology. Where the drift is fine textured, peats and peaty gley soils are dominant in valley bottoms and gentle slopes (Tetzlaff *et al.*, 2007). Where slopes are steeper or drifts are more permeable, more freely draining soils occur (Soulsby *et al.*, 1998). Strontian is partly forested, while the Allt a'Mharcaidh and Girmock are mainly characterized by moorland.

The warmest Canadian site with a mean annual air temperature of 4.9 °C is Dorset (Harp Lake 5, 1.9 km²), which occupies the southern Boreal ecozone in south-central Ontario, with a humid continental climate and long cool summers. Annual precipitation is 980 mm, with ~28% falling as snow. Bedrock is predominantly granitized biotite and hornblende gneiss and surficial geology ranges from bedrock outcrops, thin (<1-m thick) till interrupted by rock ridges, to minor till plains. Well-drained soils generally have deciduous or mixed forest, while poorly drained soils have mixed or coniferous forest. The Catamaran Brook catchment (28.7 km²) is located in New Brunswick. The Paleozoic volcanic and sedimentary basement is overlain by late Pleistocene till and glaciofluvial deposits of loamy to sandy loam texture. Average precipitation is 990 mm, 30% of which is snow. Mean annual air temperature is 5.0 °C, and vegetation consists of second-growth forest (65% coniferous and 35% deciduous). The coldest Canadian catchment with an annual air temperature of -2.2 °C is Granger Creek (7.6 km²), located in the Wolf Creek Research Basin on the fringe of the Coast Mountains, Yukon Territory. The climate is continental subarctic, with mean annual precipitation of 478 mm (40% as snow). The geological composition is primarily sedimentary, and a till mantle with thickness from centimetres to 10 m. Atop the till, soils

are capped with a surface organic layer at lower elevations ranging from 0.05 to 0.3 m. Permafrost (perennially frozen ground) underlies ~70% of the catchment. The catchment is above treeline and vegetation consists of assorted shrubs at lower elevations and tundra at higher elevation (McCartney *et al.*, 2006).

Two of the United States catchments are located in the Northeast (Hubbard Brook, New Hampshire and Sleepers River, Vermont), with HJ Andrews located in the Pacific Northwest (Oregon). Sleepers River (W9, 0.41 km²) has a mean annual air temperature of 4.7 °C and 1256 mm of precipitation, 25% of which falls as snow. Bedrock consists of quartz-mica phyllite with beds of calcareous granulite, mantled by 1–4 m of dense silty glacial till. Inceptisols and Spodosols have developed on the till in upland settings to an average depth of 0.7 m. Histosols with up to several tens of centimetres of black muck overlying the till prevail in riparian zones. Vegetation is primarily northern hardwood (Shanley *et al.*, 2004). The climate at Hubbard Brook Experimental Forest catchment (WS3, 0.41 km²) is humid continental (Likens and Bormann, 1990; Bailey *et al.*, 2003) and similar to Sleepers River with an annual air temperature of 6.4 °C. Bedrock is composed of pelitic schist overlain by glacial drift deposits, typically basal and ablation tills of varying thickness. Approximately 80% of the soils are classified as Spodosols (haplorthods), and the remaining ~20% of soils are Inceptisols. The catchment is entirely forested with typical second-growth northern hardwood species. HJ Andrews (Mack Creek, 5.8 km²) in the western Cascades of Oregon is the warmest North-Watch catchment with a mean annual air temperature of 9.2 °C. It is a steep mountainous basin with 860 m of relief. Annual precipitation is ~2500 mm that falls mostly in the winter. Only 7% of precipitation is received as snow. The geology is composed of andesitic and basaltic lava flows and soils are deeply weathered and freely draining (Dyrness, 1969; Swanson and James, 1975). Volcanic and soils are deeply weathered and freely draining. The catchments are non-glaciated and are mainly covered by coniferous forest (McGuire *et al.*, 2005).

Data and Inter-Site Comparison Metrics

The collection of multi-year continuous records for intercomparison is a particular challenge in cold regions due to difficult winter conditions that present both logistical and instrumentation obstacles. Furthermore, motivation for field measurements differs among catchments as the focus for many of the North-Watch catchments was not originally on continuous measurements. Important issues of database compilation and data harmonization were addressed to assemble 10 years of continuous daily temperature, precipitation and discharge for all catchments except Mharcaidh, which had 4 years of continuous daily data and Catamaran with 6 years. Data quality control is

conducted regularly for these well-established sites, and we believe that the data quality is usually high.

The method of data collection for precipitation and discharge varied among the catchments. At most sites, national weather networks were used supplemented by local observations. Temperature (T) and precipitation (P) at each site were either directly measured or interpolated from a nearby station. Precipitation as snow was directly measured, yet the timing and rate of melt was not computed. Discharge (Q) was determined at all sites using a local stage–discharge relationship or gauging structure (i.e. flume or weir). For Wolf Creek, salt-dilution was used during the freshet period and under-ice due to back-water effects associated with snow and ice choked conditions. Over-winter flows were estimated as a continuous recession between the final autumn measurement until the following spring initial under-ice measurement. Details are explained in all site-specific references cited above.

The long-term actual evaporation rate was determined via the water balance assuming change in storage = 0 over the length of record. Daily estimates of evaporation (E) were computed using the potential evaporation method of Hamon (1961) and transformed to actual values by a correction factor, which was chosen to match the water-balance based long-term estimate. Following this estimation of daily evaporation, accumulated storage changes (S) were calculated on a daily basis via the water balance. For each catchment and year, the 10th and 90th percentiles of the accumulated storage change values were selected and the differences computed. The median value for each catchment was used as a measure of average annual storage changes.

Both annual and monthly data were used for inter-comparison. On an annual basis, the standard deviation divided by the mean [coefficient of variation (cv)] of Q and P was determined and the ratio of their cv , cvQ_A/cvP_A was used as a measure of the degree to which streamflow is a consistent portion of precipitation and/or how closely they are coupled (Post and Jones, 2001). It is inversely related to the correlation coefficient of the annual series of Q and P , $corr(Q_A, P_A)$, in that larger cvQ_A/cvP_A have, on an average, lower $corr(Q_A, P_A)$.

As with the annual series, variation statistics of monthly fluxes provide information on seasonality and synchronicity of hydrological regimes. The cv of all monthly precipitation values (cvP_{mo}) provides information on the magnitude of difference between wet and dry seasons, whereas the cv of all monthly discharge (cvQ_{mo}) provides an indication of seasonal flow variability. To assess the degree of monthly coupling between P and Q , the ratio of their monthly coefficients of variation cvQ_{mo}/cvP_{mo} for all months was determined along with their correlation coefficients, $corr(Q_{mo}, P_{mo})$.

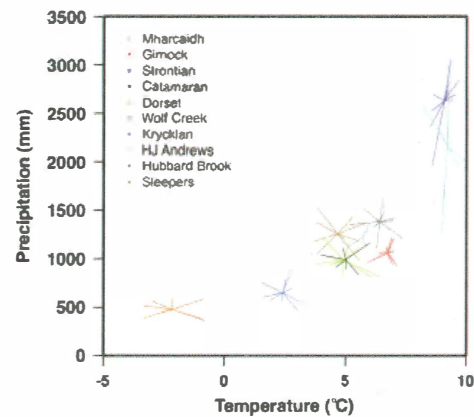


Figure 2. Binary scatter plot of mean annual temperature versus mean annual precipitation. Centroid is the mean of the annual data with lines connected to the individual years

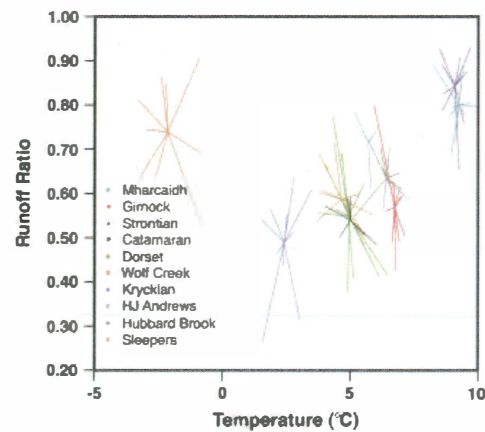


Figure 3. Binary scatter plot of mean annual temperature versus mean annual runoff ratio. Centroid is the mean of the annual data with lines connected to the individual years

To examine natural groupings of catchments based on the inter-dependence of hydrological indices, climate and topography, a principal component analysis (PCA) was completed. While exploratory in nature, PCA analyses have been used previously to map catchments into similar groupings based on hydrological and other indices, and can provide additional insight when exploring the dependency among factors (Pfister *et al.*, 2000; Monk *et al.*, 2007; Tetzlaff and Soulsby, 2008). Here, nine factors were used in the PCA: annual T , P , Q , S , cvP_{mo} , cvQ_{mo} , cvQ_{mo}/cvP_{mo} , $corr(Q_{mo}, P_{mo})$, and total relief.

Results

Annual series: hydro-climatic characterization of the North-Watch sites

Table II summarizes the mean annual indices of measured T , P and Q along with E and S as calculated above. Plots of P and annual runoff ratio (Q/P)_A versus annual

T are presented in Figures 2 and 3, respectively. Mean annual temperature ranges from a maximum of 9.2°C at HJ Andrews to -2.2°C for Wolf Creek. With regard to a general hydro-climatic characterization of the sites, on an average, colder sites are characterized by a more continental climate and exhibit a greater variability in their average annual temperature. There is a general trend of reduction in precipitation with increasing latitude, and as would be expected, stations at the western sides of the continents and more heavily influenced by a maritime climate (Strontian, HJ Andrews) have markedly greater precipitation. In terms of absolute values, annual precipitation varies most in the warmest wettest catchments, yet the coefficient of variation (cvP) does not exhibit a temperature-based trend. Discharge varies widely among the catchments, increasing in general with temperature (and is strongly related to precipitation). The variability in annual runoff as expressed by the cv does not exhibit a temperature-based trend.

Area-normalized discharge (expressed in mm) and flow statistics show the wide variability among catchments. Q50 is greatest at HJ Andrews (3.1 mm day^{-1}) and smallest at Krycklan (0.33 mm day^{-1}), and along with mean annual runoff Q95 is greater in warmer and wetter catchments. Strontian and HJ Andrews have the widest range of annual discharge (and precipitation), whereas the northerly catchments Krycklan and Wolf Creek have a relatively narrow range in annual variability of discharge. Sleepers River, Hubbard Brook, Dorset, Catamaran, Girnock and Mharcaidh all have intermediate discharge (and precipitation) characteristics.

The annual runoff ratio $(Q/P)_A$ exhibits a general increase with mean annual temperature despite increases in E because P declines with temperature. The exception is Wolf Creek, which has high runoff ratios due to low E and the widespread presence of permafrost that restricts drainage. Strontian and HJ Andrews have $(Q/P)_A$ ratios of 0.84 and 0.80 respectively, while Krycklan has the lowest $(Q/P)_A$ ratio of 0.49. Runoff ratios increase with total P as expected, again with the exception of Wolf Creek, which has the lowest P , and a high annual $(Q/P)_A$. The annual variability of runoff as expressed by the cv is closely related to the cv of precipitation, with no distinct temperature signal. cvQ_A/cvP_A shows that streamflow at HJ Andrews is closely coupled on an annual basis with precipitation, returning to the same base level at the end of the long, pronounced summer dry period regardless of winter precipitation amounts. In contrast, Dorset, Krycklan and Girnock have a large cvQ_A/cvP_A , suggesting a high inter-annual resistance and greater storage. There is no apparent influence of temperature on inter-annual variation between P and Q .

While not a direct measurement and sensitive to systematic errors in precipitation and runoff, the computed S does provide, through the water balance, a measure of

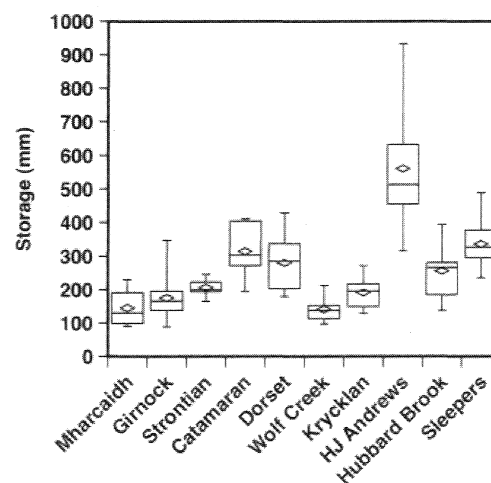


Figure 4. Box and whisker plot of annual storage change for the catchments

the influence of seasonal storage change for each catchment. Storage magnitude and variability is greatest at HJ Andrews (561 mm), which is in part explained by its deep well-drained soils and large seasonal variability in P (Figure 4). Sleepers River, Hubbard Brook, Catamaran and Dorset all have mean S values between 240 and 340 mm and similar seasonal P and Q . S is smallest at Wolf Creek, which is attributed to thin unfrozen soils, whereas the variability in S is smallest at Strontian, which of all catchments shows the least variability in the response of Q to P .

Seasonality as a metric for inter-site comparison

The monthly series of P , Q and E are shown in Figure 5. The seasonal change in P and Q along with their synchronicity varies widely among the catchments. The cv of all monthly precipitation values (cvP_{mo}) as an index for seasonality and synchronicity of hydrological regimes provides information on the magnitude of wet/dry seasons (Table III). For example, Catamaran, Sleepers River, Hubbard Brook and Dorset do not exhibit distinct wet/dry seasons, and have low cvP_{mo} ranging from 0.43 to 0.50. In contrast, HJ Andrews, Wolf Creek and Krycklan have distinct wet and dry seasons, with cvP_{mo} of 0.89, 0.70 and 0.62, respectively. Strontian is a notable exception in this pattern as it has high standard deviation of precipitation, yet its cvP_{mo} is intermediate because of large P throughout the year. Similar to P , the cv of Q (cvQ_{mo}) is a representation of the monthly variability of flows. Catchments with a large spring freshet (Wolf Creek, Catamaran, Dorset, Sleepers, Hubbard Brook, Krycklan and Catamaran) have high cvQ_{mo} , whereas those without have smaller values. The large flow variability at HJ Andrews and Strontian is not reflected by high cvQ_{mo} due to the magnitude of flows, highlighting the limitation of using the cv as a robust metric of seasonality.

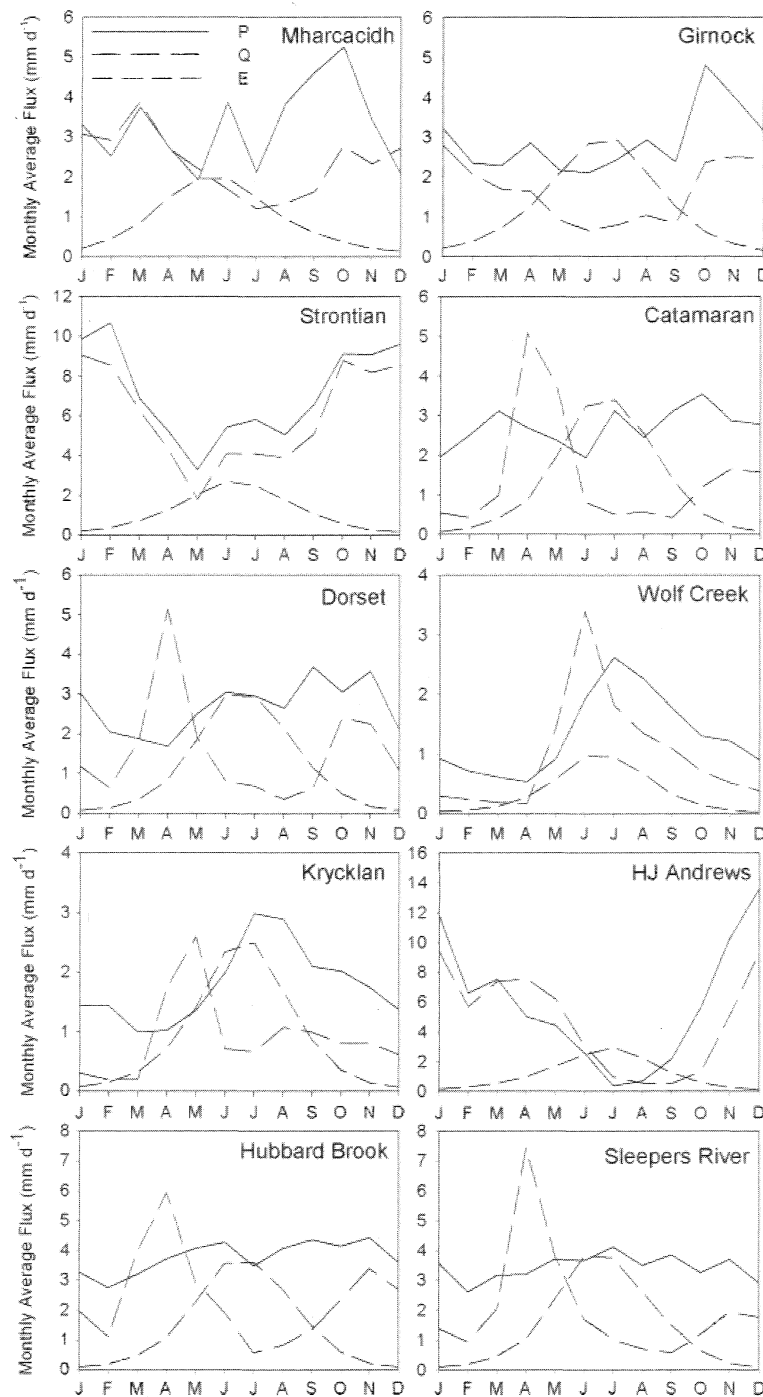


Figure 5. Monthly precipitation, runoff and evaporation for the catchments. Note that the y-axis is different for each panel

Lower values of cvQ_{mo}/cvP_{mo} as an expression of the monthly coupling between P and Q and higher $corr(Q_{mo}, P_{mo})$ indicate a greater synchronicity in P and Q . Strontian and HJ Andrews have the highest $corr(Q_{mo}, P_{mo})$ values (0.85 and 0.77). In contrast,

Dorset (0.16), Catamaran (0.21) and Sleepers (0.24) all have low $corr(Q_{mo}, P_{mo})$. cvQ_{mo}/cvP_{mo} is greatest at Catamaran and Sleepers River due to the reduced seasonality in Q compared with P , and smallest at HJ Andrews which has a very large cvP_{mo} . However, low

Table III. Coefficient of variation of average monthly precipitation (cvP_{mo}), discharge (cvQ_{mo}) and ratio of monthly discharge and precipitation (cvQ_{mo}/cvP_{mo}) for all months of record

Catchment	cv (P_{mo})	cv (Q_{mo})	$cvQ_{mo}/$ cvP_{mo}	$corr$ (Q_{mo}/P_{mo})
Mharcaidh	0.50	0.51	1.00	0.40
Girnock	0.59	0.74	1.25	0.75
Strontian	0.52	0.63	1.21	0.85
Catamaran	0.45	1.09	2.40	0.21
Dorset	0.50	1.10	2.18	0.16
Wolf Creek	0.70	1.18	1.68	0.53
Krycklan	0.63	1.13	1.80	0.35
HJ Andrews	0.89	0.89	0.99	0.77
Hubbard Brook	0.49	0.92	1.89	0.56
Sleepers	0.44	1.04	2.39	0.24

$corr(Q_{mo}/P_{mo})$ is the correlation coefficient between monthly discharge and precipitation.

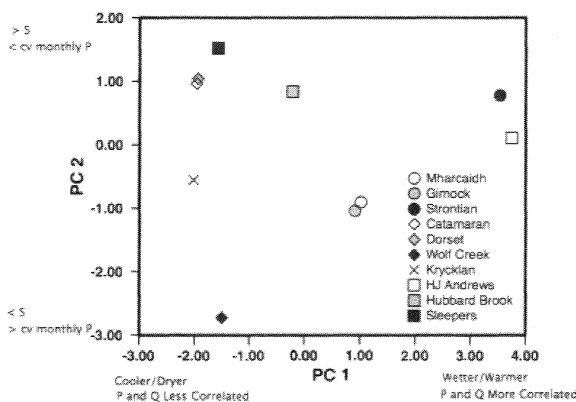


Figure 6. PCA for the ten catchments. Each catchment was characterized using the following indices: annual T , P , Q , S , cvP_{mo} , cvQ_{mo} , cvQ_{mo}/cvP_{mo} , $corr(Q_{mo}, P_{mo})$ and total relief. Indices with the highest loadings are shown adjacent to the respective axes

cvQ_{mo}/cvP_{mo} at Mharcaidh (1.03) is not reflected in a high correlation coefficient (0.42). Catchments with high winter precipitation, particularly as snow, result in low $corr(Q_{mo}, P_{mo})$, as there is significant recorded precipitation that is not released to the drainage network until spring melt.

Catchment similarity

Two principal components explain 74% of the variance in the applied PCA (Figure 6). The first principal component explains 55% of the variance and largely reflects the temperature and wetness along with $corr(Q_{mo}, P_{mo})$ and relief. The second principal component is strongly correlated with storage and the cvP_{mo} (the seasonality of the input signal). Unsurprisingly, catchments that were geographically close to one another (e.g. Sleepers, Hubbard Brook, Catamaran and Dorset or Girnock and Mharcaidh) cluster together. However, HJ Andrews and

Strontian which are geographically very far apart but similar in their westerly location on their continents and their hydro-climatic characteristics and response also cluster together. This forms the basis to identify hydro-climatic response 'types' of the catchments: warmer and wetter (and steeper) catchments with greater synchronicity (high correlation) between monthly P and Q plot to the right, whereas cooler catchments with lower $corr(Q_{mo}, P_{mo})$ plot to the left. Catchments with greater storage and less seasonal P tend to plot higher whereas, those with less storage and a greater cvP_{mo} plot lower. Wolf Creek and Krycklan separate out due to their cold and dry climates. The close association between Strontian and HJ Andrews is defined by their high precipitation and temperature and the close coupling of P and Q . Differences arise on the second component as HJ Andrews has high storage change yet a large seasonality (despite mapping high); in contrast, Strontian has low S and an intermediate cvP_{mo} .

Discussion

In catchment inter-comparisons, it can be argued that effective associations can only be achieved through normalization for climate as this allows the influence of specific catchment features (soils, topography, geology, and vegetation) to be assessed under a similar climate-forcing regime. However, we propose that climate cannot be considered an extrinsic factor that forces a catchment to respond, as many catchment properties (e.g. soils, vegetation and frozen ground status) develop over long periods in response to climate. In addition, functional traits evolve and integrate the catchment's history. Wagener *et al.* (2007) summarize classification frameworks based both on structure and on the hydro-climatic regime.

For the North-Watch catchments, precipitation decreases with decreasing temperature (increasing latitude) (Figure 2), which is consistent with the compilation of Kane and Yang (2004). This precipitation gradient results in a gradual decline in runoff ratio with latitude, (Figure 3) as the evaporation gradient is not as steep among the catchments and differences in storage capacity are not large enough to overwhelm the large differences in precipitation. For example, precipitation varies over 2000 mm among the catchments, whereas storage capacity varies only by 420 mm and evaporation 383 mm. The influence of permafrost on reducing storage and enhancing runoff (Carey and Woo, 2001) is demonstrated in Wolf Creek, which has the lowest precipitation yet is highly productive in terms of runoff.

Although there are considerable differences in the relationship between annual P and Q among the study years, there is no apparent relation between the strength of their correlation on an annual basis and T (or relief). In addition, there is no relation between inter-annual variability and seasonal variability among the catchments as reported elsewhere (Post and Jones, 2001). Other factors such as soils and basin geomorphometry not evaluated here

may play a role in controlling the inter-annual variability in the relation between P and Q . Future research will explore the inter-comparison of topographic indices and their relation to precipitation–discharge relations within North-Watch.

The influence of climate variability on catchment functioning is most strongly realized at seasonal (monthly) time-scales. However, considering the length of record, it is not possible to evaluate longer-term climate modes such as the Atlantic Oscillation, which has documented influence on catchment runoff at longer scales in the Northern Hemisphere (Dery and Wood, 2004). There is a wide disparity among the North-Watch catchments in how P inputs are translated to Q on a monthly basis and different hydro-climatic response ‘types’ of catchments could be identified: high precipitation catchments such as HJ Andrews and Strontian have large $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$, despite considerable differences in their storage capacity. For catchments with lower precipitation inputs, seasonality, relief and storage capacity play an important role in the ability of the catchment to resist transferring input water to discharge. For example, catchments with little variance in P and gentle topography (Dorset, Catamaran) have lower $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ than catchments with steep topography (e.g. Mharcaidh) due in part to their enhanced storage capacity and presumably slower drainage pathways (Soulsby *et al.*, 2009). For cold catchments with significant snow storage, a spring freshet is clearly observed that reduces the $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ and increases the $\text{cv}Q_{\text{mo}}$ and the $\text{cv}(Q_{\text{mo}}/P_{\text{mo}})$.

It is equivocal from this preliminary analysis as to why some catchments have greater ability to resist changes in P with respect to Q than others from year-to-year. However, on a seasonal basis, clear patterns emerge where snow-dominated catchments have lower $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ and higher $\text{cv}Q_{\text{mo}}/\text{cv}P_{\text{mo}}$, highlighting the 0°C threshold effect of melting snow. The influence of topography (as expressed by relief) on $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ and $\text{cv}(Q_{\text{mo}}/P_{\text{mo}})$ is also noted as the catchments with greater relief tend to have greater coupling between monthly P and Q and decreased dampening of runoff to precipitation signals, suggesting less resistance to seasonal climate variability. As expected, there was a general decline in $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ and increase in $\text{cv}Q_{\text{mo}}/\text{cv}P_{\text{mo}}$ with increasing seasonal storage change, with the exception of HJ Andrews with a high $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$ and low $\text{cv}Q_{\text{mo}}/\text{cv}P_{\text{mo}}$. The reason that HJ Andrews, with the highest S , has low resistance may in part be explained by the total magnitude of rainfall and strong seasonal signal that is able to overwhelm the storage capacity. This suggests that as precipitation increases, the monthly coupling between P and Q increases (a weak trend that is observed), and a threshold relation likely exists such that resistance becomes reduced when $P \gg S$. This also suggests that drier cooler catchments with less seasonality in P have an increased resistance as catchment

storage (both in snow and soil) is greater in relation to P throughout most of the year. The presence of permafrost in Wolf Creek affects this general trend temperature/precipitation trend as frozen ground strongly limits S , decreasing catchment resistance, particularly during the freshet period.

The degree to which catchments can respond to and/or recover from perturbations (i.e. drought, extreme precipitation) suggests their resilience. While not a complete corollary with the notion of resistance, catchments exhibit a high resilience if they are able to keep their normal functioning (translating inputs to outputs) in the light of changing inputs. Within this study, the concept provides the basis for catchment classification. Catchments such as Strontian and HJ Andrews, where $P \gg S$, have a higher resilience. This is particularly the case for Strontian where very low S (steep topography and thin soils) indicates that its functional relation between P and Q is insensitive to change. Conversely, catchments with low $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$, higher S and lower P may exhibit decreased resilience, as changes in snow storage and soil storage can strongly impact the ability of the catchment to generate runoff.

PCA (Figure 6) is a useful technique to explore catchment groupings and the issue of functional relationships. Catchments that map to the right on PC1 (Strontian, HJ Andrews, Girnock, Mharcaidh) are wetter with higher synchronicity [i.e. higher $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$], suggesting low resistance and high resilience in their input–output relationship to change. In contrast, those to the top left (Dorset, Catamaran, Sleepers, Hubbard Brook) have lower synchronicity (i.e. lower $\text{corr}(Q_{\text{mo}}, P_{\text{mo}})$), higher dampening and a greater resistance due to increased storage. The threshold relationships that exist in these catchments due to large soil and snow storage makes their resilience potentially low, as small changes in temperature may strongly affect the relationship between P and Q . The cold catchments of Wolf Creek and Krycklan have lower resistance due to their limited storage, yet their resilience in the input/output relationship is also low due to the strong seasonality of P and the snowmelt threshold that operates most strongly in these catchments.

Although preliminary, this catchment inter-comparison exercise demonstrates the important role that climate plays in the functioning of the North-Watch catchments. Despite differences in topography and soil storage among the catchments, issues of precipitation/discharge magnitude, synchronicity, temperature and precipitation phase are first-order controls on how catchments group in their functional response. While there exists considerable literature on flow metrics as a basis for inter-comparison, here we attempt to show through simple climate and water balance data and metrics at annual and seasonal time-scales that additional insight into meaningful classification can be gained (Wagener *et al.*, 2007). By establishing resilience and resistance measures of catchments,

understanding their response to future climate change can in part be addressed. Thus, international collaborative efforts such as North-Watch which are based on high-quality information and catchment hydrological functioning provide an effective means to explore the issue of hydrological change by assessing integrated responses across a wide variety of environments.

Acknowledgements

This paper had its origins in discussions at an international workshop entitled 'Climatic drivers and hydrological regimes' which was held at the Dorset field sites, Ontario, Canada, 30 August–3 September 2009. We would like to thank Drs William Quinton, Murray Richardson and Chris Spence who participated in the workshop and provided important insights into the material in this manuscript. The North-Watch project (<http://www.abdn.ac.uk/northwatch/>) is funded by the Leverhulme Trust (F/00152/AG). The authors are also grateful to those individuals and funding agencies who contributed to gathering the data set presented: Iain Malcolm, Markus Hrachowitz, Julian Dawson for their assistance in generating the data base for the Mharcaidh, Strontian and Girnock catchments. Thanks to the staff of the Dorset Environmental Sciences Centre (Ontario Ministry of the Environment) for provision of the data. Ric Janowicz of the Yukon Territorial Government is thanked for the Wolf Creek data. The HJ Andrews team would like to thank Rosemary Fanelli, Tina Garland for assistance with data assembly; John Moreau for data collection and Don Henshaw for data archiving. The USGS water, Energy and Biogeochemical Budgets (WEBB) program is acknowledged. Hubbard Brook is part of the Long-Term Ecological Research (LTER) network, which is supported by the US National Science Foundation. The Hubbard Brook Experimental Forest is operated and maintained by the USDA Forest Service, Northern Research Station, Newtown Square, PA.

References

- Adler PB, Milchunas DG, Lauenroth WK, Sala OE, Burke IC. 2004. Functional traits of graminoids in semi-arid steppes: a test of grazing histories. *Journal of Applied Ecology* **41**: 653–663.
- Archer D, Newson M. 2002. The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. *Journal of Hydrology* **268**: 244–258.
- Bailey AS, Hornbeck JW, Campbell JL, Eagar C. 2003. Hydrometeorological database for Hubbard Brook Experimental Forest: 1955–2000. USDA Forest Service, Northeastern Research Station; 36.
- Black PE. 1997. Watershed functions. *Journal of the American Water Resources Association* **33**: 1–11. DOI: 10.1111/j.1752-1688.1997.tb04077.x.
- Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23.
- Brown RD, Mote PW. 2009. The response of Northern Hemisphere snow cover to a changing climate. *Journal of Climate* **22**: 2124–2145.
- Buffam I, Laudon H, Temnerud J, Mörth CM, Bishop K. 2007. Landscape-scale variability of acidity and dissolved organic carbon during spring flood in a boreal stream network. *Journal of Geophysical Research* **112**: G01022.
- Buttle J. 2006. Mapping first-order controls on streamflow from drainage basins: the T-3 template. *Hydrological Processes* **20**: 3415–22. DOI: 10.1002/hyp.6519.
- Carey SK, Woo MK. 2001. Slope runoff processes and flow generation in a subarctic, subalpine catchment. *Journal of Hydrology* **253**: 110–129.
- Chen J, Kumar P. 2002. Role of terrestrial hydrologic memory in modulating ENSO impacts in North America. *Journal of Climate* **15**: 3569–3585.
- Clausen B, Biggs BJF. 2000. Flow variables for ecological studies in temperate streams: groupings based on covariance. *Journal of Hydrology* **237**: 184–197.
- Dery SJ, Wood EF. 2004. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophysical Research Letters* **31**: L18205. DOI: 10.1029/2004GL020729.
- Detty JM, McGuire KJ. 2010. Topographic controls on shallow groundwater dynamics: implications of hydrological connectivity between riparian zones in a till mantled catchment. *Hydrological Processes* **24**: 2222–2236. DOI: 10.1002/hyp.7656.
- Devito K, Creed I, Gan T, Mendoza C, Petrone R, Silins U, Smerdon B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes* **19**: 1705–174. DOI: 10.1002/hyp.5881.
- Dyrness CT. 1969. Hydrologic properties of soils on three small watersheds in the western Cascades of Oregon. Res. Note PNW-111. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: Portland, OR:17.
- Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution and Systematics* **35**: 557–581. DOI: 10.1146/annurev.ecolsys.35.021103.105711.
- Haines AT, Finlayson BL, McMahon TA. 1988. A global classification of river regimes. *Applied Geography* **8**: 255–272.
- Hamon WR. 1961. Estimating potential evaporation. *Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers* **871**: 107–120.
- Jones JA. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research* **36**: 2621–2642. DOI: 10.1016/j.jhydrol.2009.03.030.
- Jones JA. 2005. Intersite comparisons of rainfall-runoff processes. *Encyclopedia of Hydrological Sciences*, Anderson M (ed.) John Wiley & Sons, Ltd: Chichester: 1839–1854.
- Jothityangkoon C, Sivapalan M. 2009. Framework for exploration of climatic and landscape controls on catchment water balance, with emphasis on inter-annual variability. *Journal of Hydrology* **371**: 154–168.
- Kane DL, Yang D (ed.). 2004. *Northern Research Water Balance*. International Association of Hydrological Sciences Publication 290: Wallingford: 271.
- Lane SN, Brookes CJ, Kirkby AJ, Holden J. 2004. A network-index based version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes* **18**: 191–201.
- Leopold LB, Wolman MG, Miller JP. 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman and Co.: San Francisco, CA.
- Likens GE, Borman FH. 1990. *Biogeochemistry of a forested ecosystem*. Springer-Verlag, New York.
- McCabe GJ, Wolock DM. 2010. Long-term variability in Northern Hemisphere snow cover and associations with warmer winters. *Climatic Change* **99**: 141–153. DOI: 10.1007/s10584-009-9675-2.
- McCartney SE, Carey SK, Pomeroy JW. 2006. Intra-basin variability of snowmelt water balance calculations in a subarctic catchment. *Hydrological Processes* **20**: 1001–1016. DOI:10.1002/hyp.6125.

- McDonnell JJ, Woods R. 2004. On the need for catchment classification. *Journal of Hydrology* **299**: 2–3. DOI:10.1016/j.jhydrol.2004.09.003.
- McDonnell JJ, Sivapalan M, Vaché K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick ML, Selker J, Weiler M. 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. *Water Resources Research* **43**: 6 pp. DOI: 10.1029/2006WR005467.
- McGuire KJ, McDonnell JJ, Weiler M, Kendall C, McGlynn BL. 2005. The role of topography on catchment-scale water residence time. *Water Resources Research* **45**. DOI: 10.1029/2004WR003657.
- Monk WA, Wood PJ, Hannah DM, Wilson DA. 2007. Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications* **23**: 113–122.
- Nijssen B, O'Donnell GM, Hamlet AF, Lettenmaier DP. 2001. Hydrologic sensitivity of global rivers to climate change. *Climatic Change* **50**: 143–175.
- Olden JD, Poff NL. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* **19**: 101–121. DOI: 10.1002/rra.700.
- Pfister L, Humbert J, Hoffman L. 2000. Recent trends in rainfall-runoff characteristics in the Alzette river basin, Luxembourg. *Climatic Change* **45**: 323–337.
- Post DA, Jones JA. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Advances in Water Resources* **24**: 1195–1210.
- Potts DL, Huxman TE, Enquist BJ, Weltzin JF, Williams DG. 2006. Resilience and resistance of ecosystem functional response to a precipitation pulse in a semi-arid grassland. *Journal of Ecology* **94**: 23–30. DOI: 10.1111/j.1365-2745.2005.01060.x.
- Richter BD, Baumgartner JV, Braun DP, Powell J. 1998. A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers-Research & Management* **14**: 329–340.
- Robins NS. 1990. *Hydrogeology of Scotland*. HMSO, London.
- Schulz K, Seppelt R, Zehe E, Vogel HJ, Attinger S. 2006. Importance of spatial structures in advancing hydrological sciences. *Water Resources Research* **42**: W03S03. DOI: 10.1029/2005WR004301.
- Shanley JB, Kram P, Hruska J, Bullen TD. 2004. A biogeochemical comparison of two well-buffered catchments with contrasting histories of acid deposition. *Water Air and Soil Pollution: Focus* **4**: 325–342.
- Soulsby C, Chen M, Ferrier RC, Jenkins A, Harriman R. 1998. Hydrogeochemistry of shallow groundwater in a Scottish catchment. *Hydrological Processes* **12**: 1111–1127.
- Soulsby C, Tetzlaff D, Rodgers P, Dunn SM, Waldron S. 2006. Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: an initial evaluation. *Journal of Hydrology* **325**: 197–221.
- Soulsby C, Tetzlaff D, Hrachowitz M. 2009. Tracers and transit times: windows for viewing catchment scale storage? *Hydrological Processes* **23**: 3503–3507.
- Spence C. 2006. Hydrological processes and streamflow in a lake dominated watercourse. *Hydrological Processes* **20**: 3665–3681. DOI: 10.1003/hyp.6381.
- Swanson FJ, James ME. 1975. *Geology and geomorphology of the H. J. Andrews Experimental Forest, Western Cascades, Oregon*. Pacific Northwest Forest and Range Experimental Station: Portland, OR:14.
- Tague C, Grant G, Farrell M, Choate J, Jefferson A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change* **86**: 189–210. DOI: 10.1007/s10584-007-9294-8.d.
- Tague C, Grant GE. 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. *Water Resources Research* **45**: W07421. DOI: 10.1029/2008WR007179.
- Tetzlaff D, Carey SK. 2009. Assessing the effects of climate change on northern river basins. *Eos Transactions-American Geophysical Union* **90**: 45.
- 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, Soulsby C. 2008. Sources of baseflow in large catchments—using tracers to develop a holistic understanding of runoff generation. *Journal of Hydrology* **359**: 287–302.
- Tetzlaff D, Seibert J, Soulsby C. 2009a. Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland. *Hydrological Processes* **23**: 1874–1886.
- Tetzlaff D, Seibert J, McGuire KJ, Laudon H, Burns DA, Dunn SM, Soulsby C. 2009b. How does landscape structure influence catchment transit times across different geomorphic provinces? *Hydrological Processes* **23**: 945–953.
- Tetzlaff D, Soulsby C, Birkel C. 2010. Hydrological connectivity and microbiological fluxes between landscapes and riverscapes: the importance of seasonality. *Hydrological Processes* **24**: 1231–1235.
- Uchida T, McDonnell JJ, Asano Y. 2006. Functional intercomparison of hillslopes and small catchments by examining water source, flowpath and mean residence time. *Journal of Hydrology* **327**: 627–642. DOI: 10.1016/j.jhydrol.2006.02.037.
- Wagener T, Sivapalan M, Troch P, Woods R. 2007. Catchment classification and hydrologic similarity. *Geography Compass* **1**: 901–931. DOI: 10.1111/j.1749-8198.2007.00039.