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Comparison of threshold hydrologic response across northern catchments

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Abstract:

Nine mid-latitude to high-latitude headwater catchments – part of the Northern Watershed Ecosystem Response to Climate Change (North-Watch) programme – were used to analyze threshold response to rainfall and snowmelt-driven events and link the different responses to the catchment characteristics of the nine sites. The North-Watch data include daily time-series of various lengths of multiple variables such as air temperature, precipitation and discharge. Rainfall and meltwater inputs were differentiated using a degree-day snowmelt approach. Distinct hydrological events were identified, and precipitation-runoff response curves were visually assessed. Results showed that eight of nine catchments showed runoff initiation thresholds and effective precipitation input thresholds. For rainfall-triggered events, catchment hydroclimatic and physical characteristics (e.g. mean annual air temperature, median flow path distance to the stream, median sub-catchment area) were strong predictors of threshold strength. For snowmelt-driven events, however, thresholds and the factors controlling precipitation-runoff response were difficult to identify. The variability in catchments responses to snowmelt was not fully explained by runoff initiation thresholds and input magnitude thresholds. The quantification of input intensity thresholds (e.g. snow melting and permafrost thawing rates) is likely required for an adequate characterization of nonlinear spring runoff generation in such northern environments. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS thresholds; rainfall; snowmelt; quickflow; dynamic storage deficit; North-Watch programme

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INTRODUCTION

Understanding of the response of streams to precipitation inputs in northern headwater catchments is still limited (Tetzlaff *et al*., 2013a). In many temperate humid catchments where most of the process work has been done, hydrological threshold behaviours have been described where changes in runoff response are strongly dependent on antecedent soil moisture conditions and/or disproportional to forcing inputs across the whole possible range of inputs (e.g. Dickinson and Whiteley, 1970; Tani, 1997; Phillips, 2003; Tromp-Van Meerveld and McDonnell, 2006a; Detty and McGuire, 2010). Many studies have shown that critical values of precipitation amounts or (soil moisture) storage capacities need to be exceeded for hydrological response initiation (e.g. Whipkey, 1965; Mosley, 1979; Tani, 1997; Uchida *et al*., 2005; Tromp-Van Meerveld and McDonnell, 2006a); these precipitation input thresholds have been considered by some to be emergent catchment properties (Weiler *et al*., 2005; Lehmann *et al*., 2007) and by others as catchment hydrological signatures (Spence, 2007). Thresholds may also provide a useful tool for catchment comparison and model calibration and validation, as they facilitate the grouping of similar hydrological responses (e.g. Sivakumar, 2005; Graham and McDonnell, 2010).

While threshold detection and explanation appears to be a useful research avenue for advancing catchment process understanding, work to date has focused mostly on small catchments and hillslopes (Tani, 1997), has been

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highly qualitative in the quantification of threshold strength (Tromp-Van Meerveld and McDonnell, 2006a) and has not yet explored these dynamics in northern watersheds, as experimental work in high-latitude environments is much harder to conduct. Indeed, with only a few exceptions (e.g. Detty and McGuire, 2010; Graham and McDonnell, 2010; Penna *et al*., 2011), threshold detection studies have been performed largely at the hillslope scale given the availability of high-frequency (e.g. hourly and sub-hourly) precipitation-runoff data. The majority of threshold detection studies have dealt with rainfall events (and not snowmelt) in mostly humid temperate environments (e.g. Tani, 1997; McGlynn and McDonnell, 2003; Tromp-Van Meerveld and McDonnell, 2006a, b; Lehmann *et al*., 2007; Detty and McGuire, 2010). Event rainfall critical threshold values have been identified for specific sites, for example, 20 mm (Mosley, 1979; Tani, 1997), 23 mm (Penna *et al*., 2011), 35 mm (Whipkey, 1965) or 55 mm (Tromp-Van Meerveld and McDonnell, 2006a): it is likely that these differences in rainfall storage thresholds are controlled by catchment characteristics such as mean soil depth, depth of overburden or interception capacity of the overlying vegetation and litter layer, although those aspects are rarely reported in detail in associated publications.

In contrast to temperate environments, little information exists for northern catchments in terms of the linearity or non-linearity of their runoff responses to precipitation inputs. Several research initiatives such as the Northern Research Basins working group have been established to gain a better understanding of runoff generation processes in cold regions, particularly processes that are heavily influenced by snow, ice and frozen ground (Kane and Yang, 2004). Given the limited amount of hydrometric equipment deployed in northern catchments in comparison to temperate environments, hydrologists tended to transfer theories developed in temperate regions to cold landscapes to explain the spatio-temporal variability of runoff volume and magnitude, regardless of whether runoff generation is rainfall or snowmelt-driven (Quinton and Marsh, 1999). The transferability of traditional runoff generation theories to cold catchments is not straightforward given (i) the major differences in the control factors prevailing in low and high-latitude regions and (ii) the tremendous heterogeneity of landscapes and dominant processes even within high-latitude regions. The complexity of threshold response in northern Canadian catchments has been documented notably by Allan and Roulet (1994), Goodyear (1997), Spence and Woo (2002, 2003, and 2006) and Buttle *et al*. (2004), among others. The (ubiquitous) existence of runoff initiation thresholds and effective precipitation thresholds in northern catchments, however, remains unclear as water storage and release are not only governed by antecedent soil moisture but also snowpack and permafrost properties. Site intercomparison work is needed to quantify how hillslope or catchment characteristics might explain differences in threshold values, if they do indeed exist in northern catchments, and how rainfall and snowmelt-driven hydrological dynamics might compare in cold landscapes. This is especially important in light of projected climate changes that predict spatially variable effects on northern streamflow regimes depending on the future magnitude and onset of snowmelt runoff generation (Tetzlaff *et al*., 2013a).

Here, we explore the linearity of runoff response to precipitation inputs for nine mid-latitude to high-latitude catchments from the Northern Watershed Ecosystem Response to Climate Change (North-Watch; http://abdn.ac.uk/northwatch) programme. North-Watch is a cross-regional inter-catchment comparison initiative that aims to assess the physical, chemical and ecological response of northern catchments to climate change. Extensive temperature, precipitation and discharge data available at the daily timestep for each study catchment were processed using a degree-day methodology to differentiate rainfall from snowmelt water inputs. Hydrograph analysis was then used to identify distinct hydrological events and examine water input, dynamic water storage and runoff dynamics. Three specific questions guided the analyses: (i) Do northern catchments exhibit threshold response to precipitation inputs?, (ii) If so, is there a (significant) difference in threshold behaviours between rainfall-triggered and snowmelt-driven hydrological events?, and (iii) Which catchment characteristics best explain differences in threshold values among the sites? The overall goal was to understand how hydrological event type (rainfall-triggered *vs* snowmelt-driven) and input or water storage dynamics interplay to determine catchment runoff response patterns in mid-latitude to high-latitude environments.

METHODS

Study sites

The nine study sites are part of the North-Watch programme and were chosen as both long-term hydroclimatic and detailed topographic data were available. The catchments are located within Scotland, the United States, Canada and Sweden (Figure 1) and are among the most intensively studied long-term headwater research sites across the circum-boreal region. They span different hydroclimatic zones, including northern temperate, subarctic and boreal environments; mean annual air temperatures range from −2.2 to 9.2 °C across the sites while mean annual precipitation ranges from 478 to 2632 mm. Some of their other characteristics have been

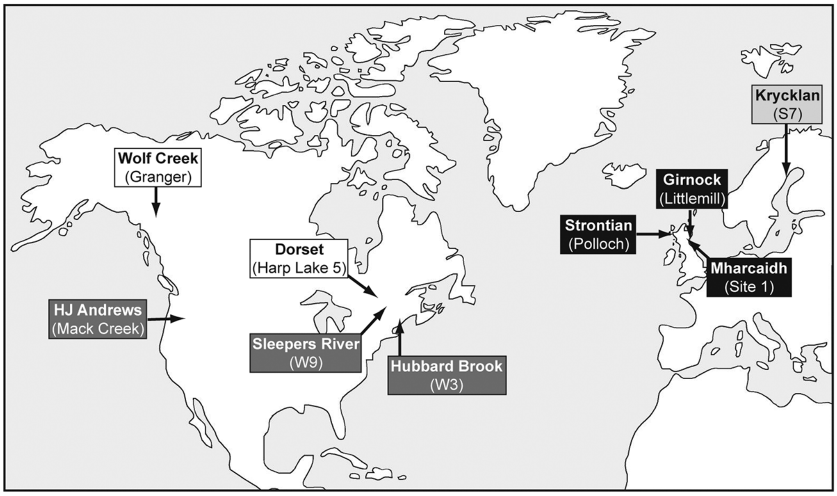

Figure 1. Location of the nine North-Watch catchments. White, light grey, dark grey and black rectangles signal Canadian, Swedish, US and Scottish catchments, respectively. Catchment names are reported in bold while specific site names (stream gauges) are mentioned in brackets

discussed in detail by Carey *et al*. (2010, 2013), Tetzlaff *et al*. (2013b), and Laudon *et al*. (2013a, 2013b) and are summarized in Table I.

Briefly, in Scotland, the Strontian site is situated in the maritime northwest, the Allt a'Mharcaidh site is in the western subarctic Cairngorms and the Girnock site is in the Northeast. The three catchments have drainage areas ranging from 8 to 30 km^2 and include steep montane regions and flat, low-lying areas. Mean annual temperatures range from 5.7 to 9.1 °C, and geology consists largely of igneous and metamorphic rocks (Robins, 1990). Typically, superficial glacial drift is superimposed on the solid geology and determine the presence of fine textured peats and peaty gleys in valley bottoms and on gentle slopes; freely draining soils such as podzols or alluvial soils are present on steeper slopes (Tetzlaff *et al*., 2007). The Strontian catchment is partly forested (mainly *Pinus sylvestris*), especially on lower slopes while the Allt a'Mharcaidh and Girnock sites are characterized by heather (*Calluna* spp.) on steeper slopes at higher altitudes and blanket bog (*Spagnum* spp.) in poorly drained areas (Bayfield and Nolan, 1998).

Two of the US sites are located in the Northeast (Hubbard Brook and Sleepers River) while a third is in the Northwest (H.J. Andrews). In the White Mountains of New Hampshire, Hubbard Brook Experimental Forest (WS3, 0.41 km^2) is covered by second-growth northern hardwood species. Short, cool summers and long, cold winters are common in this humid continental climate (Likens and Bormann, 1990; Bailey *et al*., 2003) with a mean annual air temperature of 6.4 °C and 1381 mm of precipitation, 25% to 35% of which falls as snow. Geology largely consists of pelitic schist overlain by basal and ablation tills of varying thickness. Sleepers River (W9, 0.41 km^2) in Vermont is also primarily forested with northern hardwoods of sugar maple, ash, beech and yellow birch (Shanley and Chalmers, 1999). The catchment has a mean annual air temperature of 4.7 °C and receives 1256 mm of precipitation annually, 25% of which typically falls as snow. Bedrock is mostly quartz-mica phyllite with calcareous granulite overlain by dense silty till. In Oregon, the catchment under study is the 5.8 km^2 Mack Creek in the H.J. Andrews Experimental Forest. Its geology is andesitic and basaltic lavaflows and it is mostly covered by old-growth Douglas fir (*Pseudotsuga menziesii*) forest. Mack Creek is not only the steepest catchment (with the highest relief of 860 m) among all North-Watch study sites but also the warmest and the wettest. Winters are usually wet and mild and summers rather warm and dry (Anderson, 1992) as the catchment has a mean annual air temperature of 9.2 °C and mean annual precipitation of 2158 mm. Greater than 80% of precipitation occurs from November to April, most of which falls as snow.

In Canada, focus was on the Wolf Creek catchment (Granger basin, 7.6 km^2) and one of the Dorset catchments (Harp 5, 1.19 km^2). Wolf Creek is the second most northerly catchment and is the coldest and driest (mean annual air temperature of −2.2 °C) of all North-Watch sites as it is subjected to a sub-arctic continental climate on the fringe of the Coast Mountains of Yukon. Permafrost underlies 70% of the catchment while the geology is primarily sedimentary, composed of limestone, sandstone, siltstone and conglomerate, overlain by a mantle of glacial till ranging from 1 to 4 m in thickness (Carey and Quinton, 2005). Given the cold temperatures and low annual precipitation (478 mm), vegetation generally consists of shrubs (*Salix*) and alpine tundra at higher elevations (McCartney *et al*., 2006). The Dorset site in Ontario is located in the southern Boreal ecozone

Table I. Selected characteristics of the North-Watch catchments. Evaporation and storage values are derived from annual water balance estimates (Carey *et al.*, 2010). Q5 and Q95 are the flow values that are exceeded 95% and 5% of the time, respectively

Catchment name	Gauging site	Coded name	Area (km^2)	Mean elevation (m)	Relief (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Percentage of snow (%)	Mean annual evaporation (mm)	Mean annual runoff (mm)	Q5 (mm)	Q95 (mm)	Mean annual storage change (mm)
Strontian	Polloch	STR	8	340	740	9.08	2632	4	417	2213	30.08	0.1	206
Mharcaidh	Site 1	MHA	10	704	779	5.7	1222	20	326	873	10.56	0.39	146
Girnock	Littlemill	GIR	30	405	620	6.73	1059	10	453	603	8.96	0.02	175
Hubbard Brook	W3	HUB	0.41	642	210	6.41	1381	25	497	882	17.58	0.01	255
Sleepers River	W9	SLE	0.41	604	167	4.66	1256	25	510	743	10.11	0.01	336
H.J. Andrews	Mack Creek	HJA	5.81	1200	860	9.22	2158	40	412	1744	26.54	0.29	561
Wolf Creek	Granger	WOL	7.6	1700	750	−2.15	478	45	127	352	4.84	0.07	141
Dorset	Harp Lake 5	DOR	1.9	373	93	4.94	980	28	401	577	11.16	0	263
Krycklan	S7	KRY	0.5	280	72	2.41	651	40	323	327	6.42	0	191

(Eimers *et al.*, 2008) in a humid continental climate with a mean annual temperature of 4.9 °C and precipitation of 980 mm. In contrast to Wolf Creek, soil frost is rare as it primarily occurs in wetlands and only in winter, and the bedrock is a Precambrian shield overlain by a thin layer of till. Vegetation is deciduous or mixed forest on well-drained soils while poorly drained soils have mixed or coniferous forest.

Lastly, the Krycklan catchment (site 7, 0.50 km^2) in Sweden on the Fennoscandian Shield has a mean annual temperature of 2.4 °C and is the second driest of all North-Watch sites with a mean annual precipitation value of 651 mm, 40% of which falls as snow. It is underlain by metasediments and podzol soils. The spatial distribution of vegetation species is highly dependent on topography: dry upslope areas are primarily forested with mature Scots Pine (*Pinus sylvestris*), wetlands are usually covered with *Sphagnum* and other flat, low-lying areas are covered with Norway Spruce (*Picea abies*) (Laudon *et al.*, 2013a,2013b).

Hydrograph analysis and input–output response assessment

Multi-year precipitation, temperature and discharge data were analysed to identify distinct hydrological events and relate water inputs, dynamic storage deficits (i.e. overall catchment shallow soil storage deficit – see details in the succeeding paragraphs) and runoff initiation prior to the analysis of hydrologic thresholds. For each catchment, the longest continuous measurement period available of the daily precipitation, air temperature and discharge time series was used (Table II). From the discharge time series, computer-based baseflow separations were performed. Three different baseflow estimation methods were used: the fixed interval, the sliding interval and the local minimum methods (Sloto and Crouse, 1996). As the differences between the three methods were rather small, the fixed interval baseflow estimates were retained for further analyses. Using the precipitation time series in conjunction with daily air temperature data, water inputs were separated into two categories: rainfall and snowmelt. Rainfall was assumed to be all precipitation falling when air temperature was above 0 °C. Snow accumulation was modelled by adding all precipitation when air temperature was below 0 °C. The snowpack was assumed to melt with a degree-day factor of 4 mm $°C^{-1}$ day^{-1} when air temperature was above 0 °C (Juston *et al.*, 2009). The uniform threshold temperature and degree-day factor across all sites were used for simplicity and because of the lack of consistent energy balance data with which to estimate snowmelt.

To delineate hydrological events for all North-Watch sites, the following rules were applied:

Table II. Data used for the identification of hydrological events for the North-Watch sites

Catchment name	Length of daily rainfall-runoff record used	Total number of events identified	Number of rainfall-only events	Number of snowmelt-driven events
Strontian	From 2 July 1989 until 12 December 1996	161	154	7
Mharcaidh	From 1 January 1990 until 30 July 1994	109	66	43
Girnock	From 1 January 1972 until 18 March 1994	543	370	173
Hubbard Brook	From 1 October 1958 until 30 September 2007	1080	663	417
Sleepers River	From 1 October 1991 until 20 May 2001	206	112	94
H.J. Andrews	From 17 October 1998 until 21 September 2004	105	61	44
Wolf Creek	From 8 April 1998 until 4 October 2008	82	52	29
Dorset	From 1 November 1976 until 29 April 2002	498	304	194
Krycklan	From 5 October 1990 until 31 December 2007	269	158	111

(i) A hydrological event is defined as the occurrence of a water input event followed by a runoff event;
(ii) The beginning of a water input event is defined by a day with non-zero water input (i.e. water input ≥1 mm) after a minimal 1-day dry period;
(iii) The beginning of a hydrological event corresponds to the beginning of a water input event;
(iv) The beginning of the associated runoff event is defined by the first initial hydrograph rise after the beginning of the water input event;
(v) The end of a water input event is defined by a day with precipitation input less than 1 mm;
(vi) The end of a runoff event is defined by a day at the end of a recession period with no water input or less than a 15% difference between the daily baseflow and the daily discharge values;
(vii) The end of a hydrological event corresponds to the end of a runoff event.

Given the use of rainfall and snowmelt water inputs, two types of hydrological events could be discriminated: rainfall-triggered events (i.e. rain >0, snowmelt = 0), and snowmelt-driven events (i.e. snowmelt >0, with occasional rain >0 as well). Beyond the rainfall *versus* snowmelt event classification, no discrimination was made between rain-on-snow events and radiation-driven melt events. Across all datasets, the identified water input events always led to a discharge increase, albeit sometimes very small. Some hydrological events were associated with a runoff coefficient (ratio of total runoff to total water input) >100%: these events were retained for further analyses only if they involved non-zero snowmelt water inputs to justify such high runoff coefficient values.

Once all hydrological events were identified, the following state variables were calculated:

- W_{input} is the sum of all water inputs (rainfall and snowmelt) for the duration of an event;
- $W_{storage}$ is the amount of water input required before runoff starts. Building upon the Soil Conservation System basic rainfall-runoff equation, here $W_{storage}$ is computed as the initial abstraction: the sum of all water inputs (rainfall and snowmelt) that occur between the beginning of the water input event and the initial rise in the storm hydrograph (e.g. Steenhuis *et al*., 1995; Lyon *et al*., 2004). The initial abstraction can therefore be seen as dynamic storage and be used as a proxy measure for the overall catchment shallow soil storage deficit prior to each event;
- Quickflow is the difference between the discharge and the baseflow time series, and Q_{flow} is the sum of all quickflow produced between the beginning and the end of a runoff event.

To estimate $W_{storage}$ (i.e. the initial abstraction) from the event hyetographs and hydrographs, only hydrological events with a minimum 1-day delay between the start of the water input event and the initiation of runoff response were considered; doing so made it possible to avoid dealing with high frequency (hourly), short-term input–output dynamics, which are not well captured by daily data. For each catchment, Q_{flow} was plotted against both W_{input} and then against W_{input}–$W_{storage}$, in both cases separately for rainfall-triggered and snowmelt-driven events (i.e. four plots in total). The variable W_{input}–$W_{storage}$ was used as it represents the effective precipitation after the overall catchment storage deficit has been overcome. Given the size of the catchments considered, the routing of effective precipitation to the catchment outlet was assumed to occur rather quickly (within hours) and therefore considered instantaneous for the selected data resolution (i.e. daily time scale).

Several recent studies have shown examples of nonlinear hydrological response with relationships that are reminiscent of a hockey stick shape (e.g. Tani, 1997; Weiler *et al.*, 2005; Detty and McGuire, 2010; Graham and McDonnell, 2010). Given the presence of a critical value (i.e. a threshold) of water inputs, zero or low runoff is observed below the critical value, whereas a strong linear correlation exists between the runoff response and the water inputs above the threshold. The presence (or absence) of thresholds in the hydrological response of the North-Watch catchments was visually assessed in two ways: the relationship between Q_{flow} and W_{input} was used to detect runoff initiation thresholds, while the relationship between Q_{flow} and W_{input}–$W_{storage}$ was used to detect effective input thresholds. Both types of thresholds were identified based on the clearest slope change or break in slope in input–output scatter plots. Three metrics were then used to characterize catchment hydrological behaviour at each site:

- The Spearman rank correlation coefficient $r_{Spearman}$ between the output variable (Q_{flow}) and the input variable (W_{input} or W_{input}–$W_{storage}$); it was computed to measure the strength of the relationship between water inputs, dynamic storage deficits and runoff response at the catchment outlet, and its statistical significance ($p < 0.05$) was assessed;
- The threshold value, when it was identifiable from the input-output scatter plots; and
- The coefficient of determination R^2 between input and output values above the threshold value (when applicable).

The Spearman rank correlation coefficient $r_{Spearman}$ was determined for all data, whereas R^2 values were only computed for data subsets above the threshold. Since the hockey stick conceptualization assumes a strong linear correlation between the runoff response and the water inputs above the threshold, the R^2 is the Pearson correlation coefficient to the power of 2; in our study, it was strongly correlated to the slope of the best-fit regression line and a good indication of the catchment efficiency to produce runoff.

Catchment controls

Spearman rank correlation coefficients were also calculated between the three metrics of catchment hydrological behaviour and a range of hydroclimatic and topographic catchment properties (Table III). This was done to investigate which catchment characteristics might explain any differences in hydrological behaviour among the sites (research question (iii)). These correlations between catchment characteristics and the three metrics of hydrological behaviour are hereafter referred to as $corr_{catchment}$ to distinguish them from the Spearman rank correlation coefficient ($r_{Spearman}$) that is used to measure the strength of the input–output relationships. The topographic properties described in Table III were derived from Digital Terrain Models (DTMs) with a pixel resolution of 10 m available for all nine sites. Briefly, each catchment's relief was computed as the difference between the minimum and maximum elevation scaled by the squared root of the catchment area. The terrain slope was estimated using both the D8 (Quinn *et al.*, 1991) and the MD∞ (Seibert and McGlynn, 2007) flow direction algorithms. After surface topography-driven flow paths were determined for each DTM pixel based on the direction of steepest descent, four indices were derived: the elevation above the stream, the distance from the stream, the average gradient along the flow path to the stream and the ratio of the flow path length to the flow path gradient that was used as a proxy for travel times (Gardner and McGlynn, 2009). The downslope index (Hjerdt *et al.*, 2004) is defined as the gradient towards the closest point at least 5 m (in altitude) below a certain point while the upslope area draining through each pixel was calculated using the MD∞ algorithm (Seibert and McGlynn, 2007). Two variants of the topographic wetness index (Beven and Kirkby, 1979) were considered both using the upslope area per unit contour length divided (i) by the local slope in one case and (ii) by the downslope index in the other case. All DTM-based indices were aggregated into one value for each catchment using the catchment-wide median value. Lastly, the median sub-catchment area was computed as an indicator of catchment drainage structure (McGlynn and Seibert, 2003). For all catchments, the stream network was defined using a 5 ha accumulated area threshold for stream initiation. The median of the local catchment areas of all stream pixels upstream of the catchment outlet was then estimated (McGlynn and Seibert, 2003; McGlynn *et al.*, 2003).

RESULTS

Visual identification of thresholds

Scatter plots of Q_{flow} *versus* W_{input} for rainfall-triggered and snowmelt-driven events are presented in Figures 2 and 3, respectively, while scatter plots of Q_{flow} *versus* W_{input}–$W_{storage}$ are presented in Figures 4 and 5. By

Table III. Catchment characteristics tested against the three metrics of hydrological behaviour (i.e. $r_{Spearman}$ between hydrological inputs and outputs, threshold value and R^2 values for data above the threshold value)

Variable name	Description
MeanTemperature	Mean annual daily temperature (°C)
MeanPrecipitation	Mean annual total precipitation (mm)
PrctSnow	Mean percentage of total annual precipitation that falls as snow
MeanEvaporation	Mean annual total evaporation (mm); computations involved using the potential evaporation formula of Hamon (1961) and deriving actual values using a correction factor (Carey *et al*., 2010)
MeanStorage	Mean annual storage (mm) derived using annual water balance estimates (Carey *et al*., 2010)
Area	Catchment drainage area (km^2)
MeanElevation	Mean elevation value (m) computed over the whole catchment area
Relief	Catchment relief (m)
BFI	Baseflow index – the long-term ratio of total baseflow to total streamflow
FDCS_lowflow	Slope of the flow duration curve computed between the 70th and the 100th percentiles
FDCS_intermediateflow	Slope of the flow duration curve computed between the 30th and the 70th percentiles
FDCS_highflow	Slope of the flow duration curve computed between the 0th and the 30th percentiles
ElevationAboveStream	Median elevation above the stream (m)
DistanceFromStream	Median flow path distance to the stream (m)
GradientToStream	Median gradient to the stream (m)
TransitTimeProxy	Median value of the ratio of flowpath length to flowpath gradient
D8Gradient	Median terrain slope computed using the D8 flow algorithm
DinfGradient	Median terrain slope computed using the D∞ flow algorithm
d5	Downslope index; median value of the gradient towards the closest point, which is at least 5 m (in altitude) below a target catchment pixel
SubcatchmentArea	Median sub-catchment area (km^2)
Upslope area	Median upslope area (km^2)
TWI	Median value of $\ln(a/\tan\beta)$ where a is the upslope area per unit Contour length and $\tan\beta$ is the D8 gradient for each catchment pixel
TWId5	Same as the TWI except that the downslope index gradient (5 m) is used as a slope surrogate instead of the D8 gradient

working with two series of plots, the inclusion of a storage proxy variable in the scatter plots in Figures 4 and 5 was evaluated with regard to its ability to improve the strength of the relationships between input and output hydrological variables. For rainfall-triggered events, inter-catchment differences could be observed in the relationship between Q_{flow} and W_{input}; indeed, a linear plot was obtained for the Strontian site while a clearer nonlinear curve was associated with the Sleepers River site and a large scatter was encountered for the Dorset site (Figure 2). Some catchments also exhibited differences in hydrological response between input types, as was the case for the Wolf Creek site where the overall scatter pattern associated with rainfall-triggered events was significantly different from that associated with snowmelt-driven events. Conversely, for the Hubbard Brook site, there was no significant difference between the scatter pattern associated with rainfall-triggered events and the pattern associated with snowmelt-driven events. Regardless of the input type considered, higher Spearman rank correlation coefficients ($r_{Spearman}$) were found when W_{input}–$W_{storage}$ (Figures 4 and 5) rather than W_{input} (Figures 2 and 3) was the dependent variable; this reflects a slightly better characterization of hydrological response in all nine North-Watch catchments when a proxy of dynamic storage was used. For the Strontian catchment, for example, $r_{Spearman}$ values were 0.91 and 0.88 with and without consideration of the storage component, respectively (Figures 2 and 4). Nonlinear input–output relationships somehow reminiscent of the hockey stick shape were dominant for all catchments, and the linear relationship observed for Strontian could be equated to a hockey stick shape with a very small (near zero) threshold (Figure 4). At the end of the visual assessment procedure, some patterns of hydrological response were characterized as unclear (Table IV) and were often associated with $r_{Spearman}$ values below 0.6 (e.g. Mharcaidh and Wolf Creek sites, Figure 2).

Table IV summarizes the threshold values identified from a visual assessment of the scatter plots; that visual assessment was highly subjective given absent, multiple or very subtle breakpoints in most plots. Nevertheless, the identified threshold values were highly variable between catchments: for rainfall events, they ranged from 50 to 100 mm (median value: 80 mm) when the storage deficit was not taken into account and from 36 to 80 mm (median value: 55 mm) when the storage deficit was considered. Threshold values for snowmelt events were noticeably higher: they ranged from 25 to 180 mm, with a median value of 120 mm when the storage deficit was not

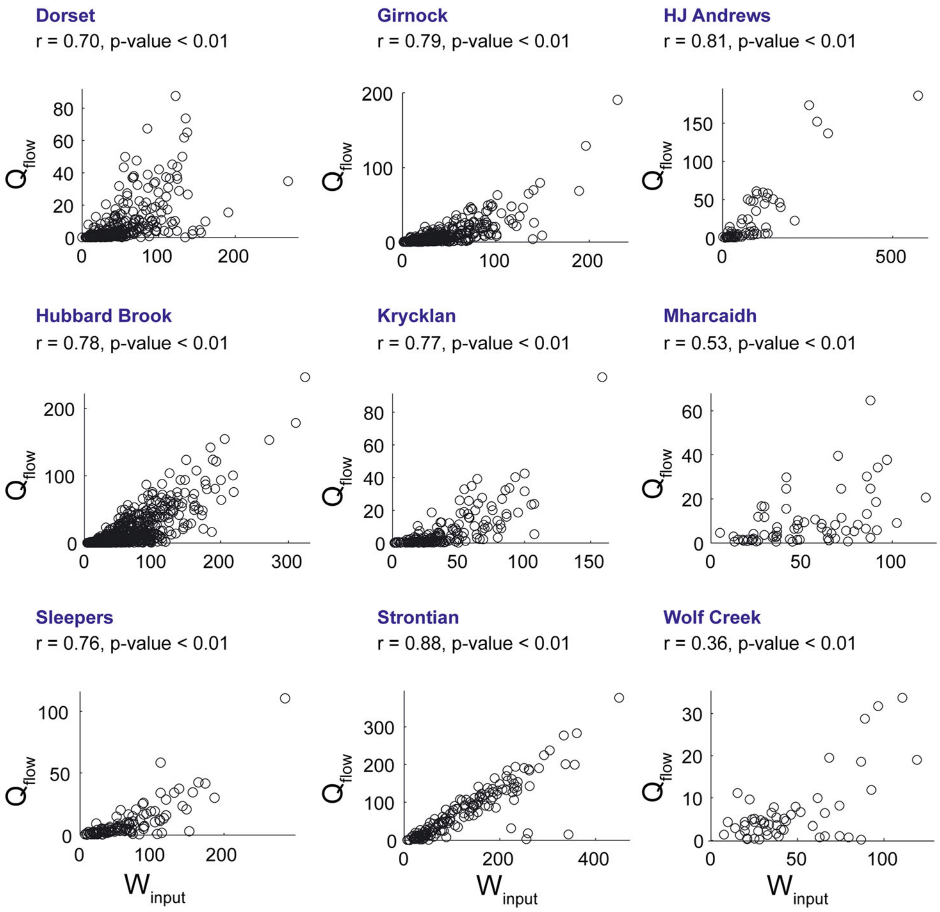

Figure 2. Total quickflow (Q_{flow}, mm) *versus* total water input (W_{input}, mm) in the nine North-Watch catchments for rainfall-triggered events. The Spearman rank correlation coefficient ($r_{Spearman}$, abbreviated as 'r') and its associated p-value are reported

considered and 85 mm when the storage deficit was considered (Table IV).

Differences between rainfall-triggered and snowmelt-driven events

The three metrics used to characterize catchment hydrological behaviour at each site (i.e. $r_{Spearman}$, the threshold value and the R^2 value above the threshold) are reported in Figures 2–4 and Tables IV and V. The threshold characterization of hydrological response was weaker for snowmelt-driven events than it was for rainfall-triggered events. Indeed, for snowmelt-driven events, the mean Spearman rank correlation coefficient among all sites was 0.59 without and 0.69 with consideration of the storage deficit (Figures 3 and 5, respectively). In contrast, the mean $r_{Spearman}$ for rainfall-triggered events among all sites was 0.70 without and increased to 0.78 with the storage deficit taken into account (Figures 2 and 4, respectively). Apart from the Girnock and the Mharcaidh catchments, for which snowmelt-driven threshold values were systematically smaller than their rainfall-driven counterparts, snowmelt-driven thresholds were usually larger than rainfall-driven ones by a factor of 1.3 to 3.4 (Table IV).

For rainfall-triggered events with or without consideration of the storage deficit, the highest R^2 values above the threshold were found for Sleepers River, H.J. Andrews, Hubbard brook and Wolf Creek (Table V). For snowmelt-driven events, however, R^2 values above the threshold were generally low or not computed because of a non-identifiable threshold. One exception was the Sleepers River site for which the R^2 above the threshold exceeded 0.6 for both rainfall and snowmelt events, regardless of whether the storage deficit was considered or not. All other catchments were associated with R^2 above the threshold of less than 0.5 for snowmelt events (Table V).

Catchment controls on hydrological behaviour

For each type of event, the catchments for which a threshold could not be identified were excluded from the correlation analyses involving those metrics. In spite of the small sample sizes (five to nine sites), some significant

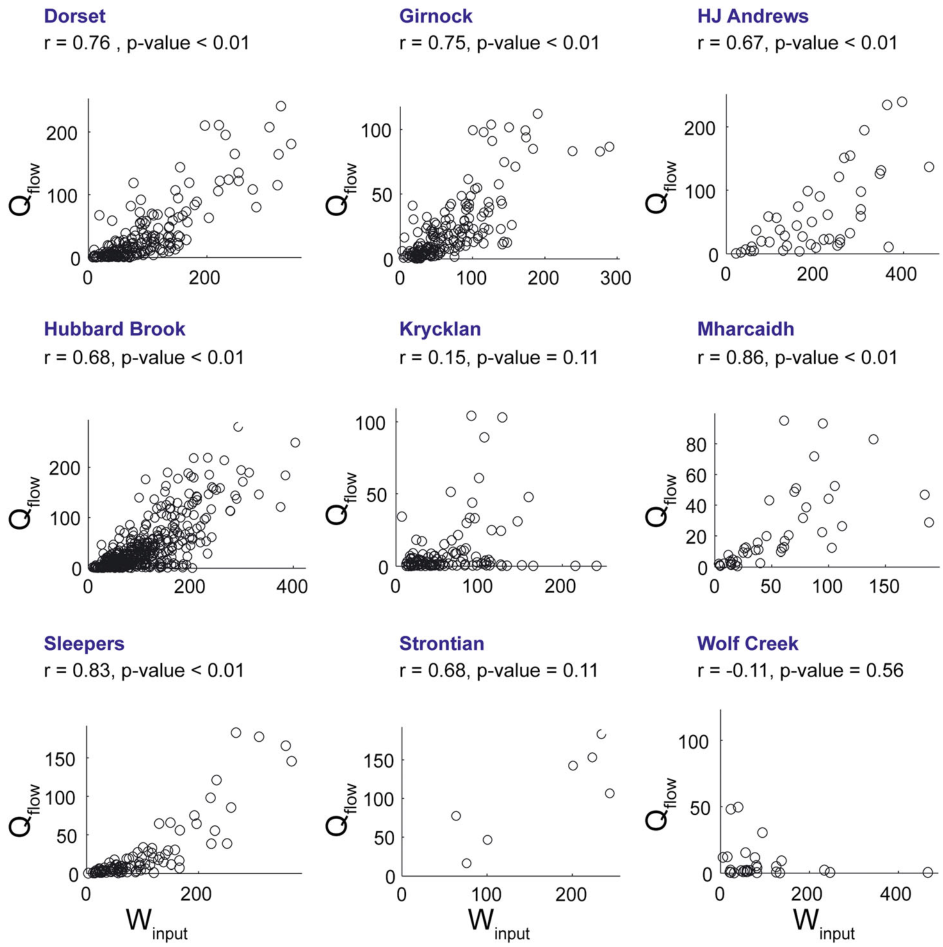

Figure 3. Total quickflow (Q_{flow}, mm) *versus* total water input (W_{input}, mm) in the nine North-Watch catchments for snowmelt-driven events. The Spearman rank correlation coefficient ($r_{Spearman}$, abbreviated as 'r') and its associated p-value are reported

correlations were observed between the three metrics of catchment hydrological behaviour and some hydroclimatic and topographic catchment properties of the North-Watch sites (Table VI). For rainfall-triggered events, regardless of whether the storage deficit ($W_{storage}$) was considered, $r_{Spearman}$ was positively linked to the median flow path distance to the stream ($corr_{catchment} = 0.81$ and 0.83, p-value < 0.05). When $W_{storage}$ was not considered, $r_{Spearman}$ values were positively related to catchment mean elevation ($corr_{catchment} = 0.71$, p-value < 0.05) while the rainfall threshold value was positively correlated with mean temperature ($corr_{catchment} = 0.66$, p-value < 0.05). When $W_{storage}$ was considered, however, the strength of input–output relationships was especially high for high relief catchments ($corr_{catchment} = 0.67$, p-value < 0.05), and the rainfall threshold value was positively correlated with the median sub-catchment area ($corr_{catchment} = 0.81$, p-value < 0.05). A few significant catchment controls were also identified for metrics of hydrological behaviour for snowmelt-driven events; however, they should be interpreted with caution given the more uncertain identification of thresholds generally for those events. For instance, when $W_{storage}$ was not taken into account, the water input (rain + snowmelt) threshold values were positively correlated with the catchment mean elevation ($corr_{catchment} = 0.66$, p-value < 0.05). The strength of the input–output relationship was also positively correlated with the median sub-catchment area ($corr_{catchment} = 0.88$, p-value < 0.05). The R^2 of input–output data above the threshold was correlated with a limited number of catchment controls: statistically significant negative correlations were notably present with the BFI and two slope segments of the catchments' flow duration curves (Table VI).

DISCUSSION

Hydrological insights from threshold detection in northern catchments

Storage deficit conceptualization. This study sought to better understand one key aspect of catchment nonlinear behaviour: the threshold precipitation-discharge response

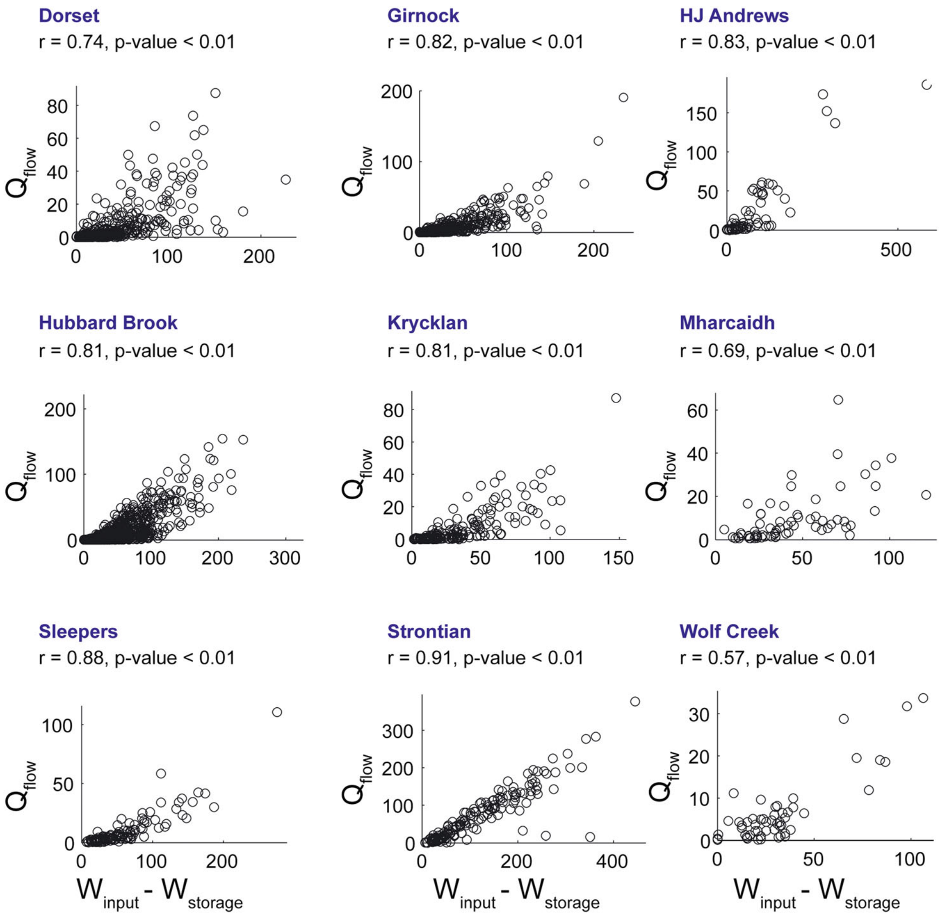

Figure 4. Total quickflow (Q_{flow}, mm) *versus* effective water input (W_{input}–$W_{storage}$, mm) in the nine North-Watch catchments for rainfall-triggered events. The Spearman rank correlation coefficient ($r_{Spearman}$, abbreviated as 'r') and its associated p-value are reported

in northern catchments – with and without snowmelt influence. Such thresholds reflect the integration of various levels of catchment complexity (Zehe and Sivapalan, 2009) and conceptually they indicate when a critical value in a hydrological state variable becomes exceeded, and a rapid flow generation mechanism responsible for event runoff is initiated. This contrasts with the times when the same hydrological state variable has a value below the threshold and the rapid flow-producing mechanisms are switched off or are less active (O'Kane and Flynn, 2007). As the memory of these switches is local in both space and time (O'Kane and Flynn, 2007), the challenge is to understand the controls exerted on thresholds when predicting catchment-scale hydrologic response across geographic regions.

For the range of mid-latitude to high-latitude northern catchments considered here, the visual identification of thresholds was useful for characterizing catchment hydrological behaviour with and without the consideration of dynamic water storage dynamics (or antecedent wetness conditions). That approach is similar to that adopted by Detty and McGuire (2010) who plotted total quickflow against the sum of gross precipitation and an antecedent soil moisture index (ASI). They found that the input–output relationships were stronger and easier to characterize when the ASI was considered in addition to gross precipitation. We found that the strength of the input–output relationships (i.e. the Spearman rank correlation coefficient, $r_{Spearman}$) was slightly greater when the difference W_{input}–$W_{storage}$ was used as the hydrological input variable rather than W_{input}. It is, however, worth noting that the assumption of instantaneous (i.e. sub-daily) routing might be incorrect, and hence the variable $W_{storage}$ might capture delays related to both storage deficit satisfaction and catchment routing rather than delays related to storage deficit satisfaction only.

This study dealt only with runoff initiation thresholds and input magnitude (i.e. effective precipitation input) thresholds while input intensity thresholds were ignored. Indeed, storage capacity (or storm amount) thresholds are often associated with saturation excess flow mechanisms while rainfall intensity thresholds can be associated with infiltration excess flow mechanisms, and their differenti-

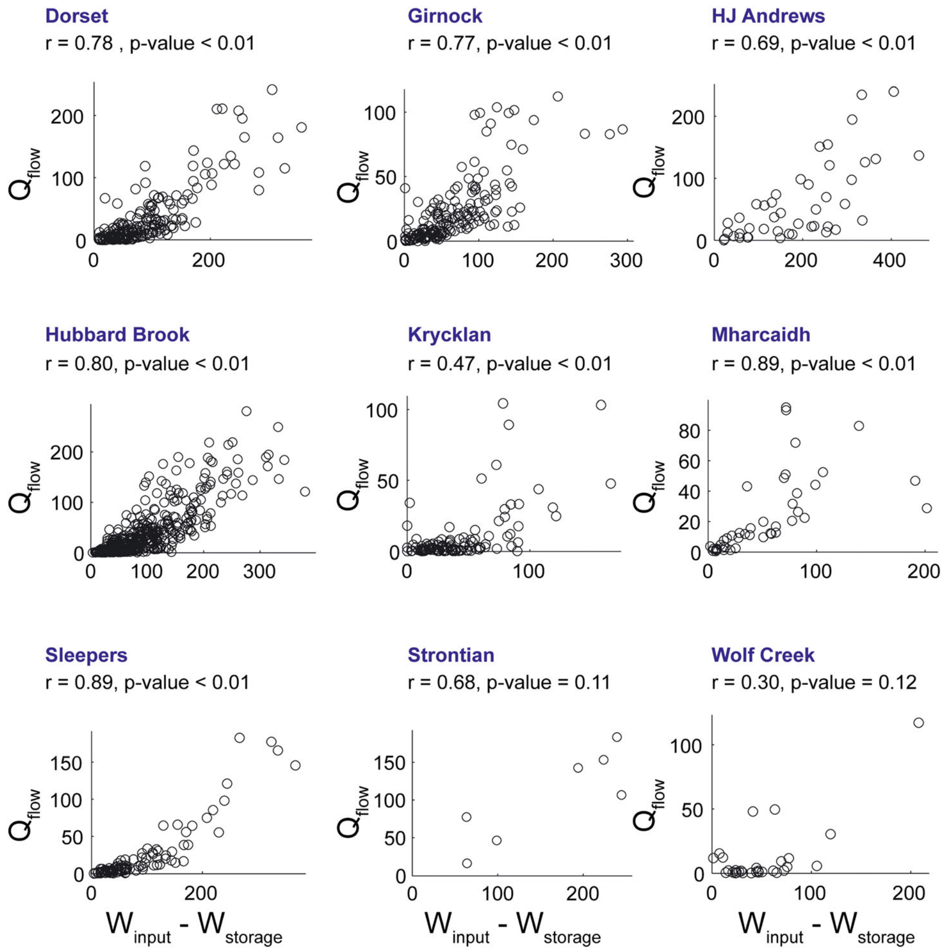

Figure 5. Total quickflow (Q_{flow}, mm) *versus* effective water input (W_{input}–$W_{storage}$, mm) in the nine North-Watch catchments for snowmelt-driven events. The Spearman rank correlation coefficient ($r_{Spearman}$, abbreviated as 'r') and its associated p-value are reported

ation is not always straightforward (McGrath *et al*., 2007). Past work has been conducted in humid temperate, forested catchments with very high soil infiltration capacities (Tromp-Van Meerveld and McDonnell, 2006a; Graham and McDonnell, 2010) where rainfall intensity was examined but had little effect on threshold values of runoff production (as suggested by Hewlett and Hibbert, 1967). Nevertheless, some of the North-Watch catchments (Krycklan, Sleepers River) develop conditions where infiltration excess runoff could occur, such as runoff over frozen ground (Shanley and Chalmers, 1999; Laudon *et al*., 2007); these effects could not be considered in the present study because of the lack of empirical data necessary for all sites.

Comparison of rainfall and snowmelt events. No clear input–output pattern could be discerned for some catchments (Figures 2, 3 and 5, Table IV) and it was difficult to assess whether this reflected a process reality or a data/methodological problem, especially regarding the degree-day method used to approximate snowmelt inputs and or the criteria used to define rainfall-triggered and snowmelt-driven events across all nine sites. It is likely that degree-day methods worked better for warmer sites with snowpacks near 0 °C, in contrast to colder sites (e.g. Krycklan, Wolf Creek) where snowpack energetics have a greater influence on the hydrological cycle. Such differences were not taken into account in the current study. The use of similar criteria for the definition of hydrological events across all nine sites was also problematic as it occasionally resulted in very large event precipitation amounts (e.g. up to 100 mm for single events at Dorset and up to 200 mm at Wolf Creek). These corresponded to compound hydrographs produced by a succession of smaller events rather than single hydrograph peaks, and this raised the issue of how hydrological events should be defined under contrasting conditions within inter-site comparisons. While it may have been beneficial to use site-specific and event type-specific (rainfall-triggered *vs* snowmelt-driven) criteria to divide precipitation and runoff events, the objective here was only to transfer the methodology from temperate

Table IV. Visually identified thresholds for the North-Watch sites. A threshold value is reported when a nonlinear hydrological response can be discerned in Figures 2–5; the term 'linear' is used when a linear hydrological response (i.e. no inflection point) is detected, and the term 'unclear' is used when no definite hockey stick pattern can be observed. For linear responses, a low threshold value of 1 mm (corresponding to the minimum precipitation event size) was used for subsequent correlation analyses

	Threshold values (when they exist)			
	Hydrologic response		Hydrologic response and storage deficit	
	Rainfall-triggered (Figure 2)	Snowmelt-driven (Figure 3)	Rainfall-triggered (Figure 4)	Snowmelt-driven (Figure 5)
Dorset	~50 mm	~170 mm	~50 mm	~150 mm
Girnock	~80 mm	~60 mm	~60 mm	~50 mm
H.J. Andrews	~80 mm	Unclear	~60 mm	Unclear
Hubbard Brook	~90 mm	~120 mm	~80 mm	~110 mm
Krycklan	~50 mm	Unclear	~40 mm	~60 mm
Mharcaidh	Unclear	~30 mm	~36 mm	~25 mm
Sleepers	~100 mm	~180 mm	~80 mm	~180 mm
Strontian	Linear (1 mm)	Linear (1 mm)	Linear (1 mm)	Linear (1 mm)
Wolf Creek	Unclear	Unclear	~40 mm	Unclear

Table V. R^2 values above the threshold for the nine North-Watch catchments. Asterisks (*) flag catchments and event types for which no statistically significant R^2 values above the threshold could be computed either because of the absence of a threshold or because of insufficient data (fewer than three event points above the threshold)

	R^2 values above the threshold			
	Hydrologic response		Hydrologic response and storage deficit	
	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven
Dorset	0.12	0.15	0.15	0.21
Girnock	0.59	0.39	0.56	0.47
H.J. Andrews	0.66	*	0.70	*
Hubbard Brook	0.54	0.40	0.61	0.48
Krycklan	0.53	*	0.39	0.18
Mharcaidh	*	0.14	0.14	0.13
Sleepers	0.90	0.79	0.65	0.7
Strontian	*	*	*	*
Wolf Creek	*	*	0.81	*

environments to higher latitude catchments. The use of daily rather than hourly or sub-hourly precipitation and discharge values was also dictated by data availability and built upon a previous threshold identification study at the catchment scale at the Maimai and HJ Andrews sites (i.e. Graham and McDonnell, 2010) – the criteria used for the delineation of water input events in the current study were similar to those used by Graham and McDonnell (2010) in their definition of storm events. We acknowledge that the use of daily data, as well as the sole selection of hydrological events with a minimum 1-day delay between the start of the water input event and the initiation of runoff response, has likely biased the present analysis: because flashy events occurring at the scale of hours were effectively discarded, the identified threshold dynamics are only applicable to longer duration events. Clearly, more research is needed: provided the availability of sub-daily weather and hydrometric data, a sensitivity analysis could be conducted to assess the identifiability of hydrologic thresholds depending on event definition criteria.

Although nonlinear behaviour associated with rainfall-triggered events was identified for more than half of the nine investigated catchments (e.g. Figure 4), snowmelt-driven events were problematic: the common conceptualization of nonlinear hydrological behaviour, namely the hockey stick-like input–output relationship, appeared to work fairly well for rainfall-triggered events but not for snowmelt-driven events. In some cases, the lack of clear input–output

Table VI. Spearman rank correlation ($corr_{catchment}$) between the three metrics of hydrological behaviour and catchment properties. Reported Spearman rank correlation coefficients are significant at the 95% statistical level

	Spearman r				Threshold value				R^2 above the threshold value			
	1Hydrologic response		Hydrologic response and storage deficit		Hydrologic response		Hydrologic response and storage deficit		Hydrologic response		Hydrologic response and storage deficit	
	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven	Rainfall-triggered	Snowmelt-driven
MeanTemperature					0.66							0.73
MeanPrecipitation												
PrctSnow												
MeanEvaporation												
MeanStorage												
Area												
MeanElevation	0.71					0.66						
Relief			0.67									
BFI												−0.72
FDCS_lowflow									−0.66			
FDCS_intermediateflow									−0.66			
FDCS_highflow												−0.72
ElevationAboveStream												
DistanceFromStream	0.81		0.83									
GradientToStream												
TransitTimeProxy												
D8Gradient												
DinfGradient												
d5												
SubcatchmentArea				0.88			0.81					
UpslopeArea												
TWI												
TWId5												

relationships with snowmelt-driven events is likely a true reflection of different physical processes. For instance, the Girnock and the Mharcaidh catchments were the only ones for which snowmelt-driven threshold values were systematically smaller than their rainfall-driven counterparts (Table IV), and this might be explained by the fact that the two Scottish catchments have the smallest and most transient snowpacks, hence the lack of potential for snowpack storage of early melt events. Also, snowfall usually occurs in the wettest winter months in the two Scottish catchments when there is little available storage in the soil.

Catchment controls. Despite the useful case studies published to date, work until now has not explored any tangible rules to up-scale or down-scale threshold values based on drainage basin properties. The work reported here shows some statistically significant correlations between hydrological behaviour and hydroclimatic or physical catchment properties (Table VI) that appear to have a physical basis. For instance, it could be inferred from Table VI that for rainfall-triggered events, the greater the median flow path distance to the stream, the higher the r_{Spearman} for rainfall-triggered events – illustrating the strength of the hydrological input–output relationship. Flow path distance to the stream is a good surrogate measure for hydrologic proximity, which is a precursor to identifying which parts of the catchment are the most likely to be connected to the channel and contribute to streamflow (Ali and Roy, 2010). It can be hypothesized that the greater the median flow path distance to the stream, the more likely that remote catchment areas will be connected to the stream when specific hydrological conditions are reached or exceeded; hence the stronger the input–output relationship and the weaker the threshold effect. When dynamic storage deficits were not considered, catchments with higher mean temperatures were also associated with greater rainfall thresholds. This correlation needs to be interpreted with caution because temperature and precipitation are highly correlated for the North-Watch catchments (Carey *et al*., 2010). In the absence of water limitation, one hypothesis is that catchments in warmer climates are subjected to greater evaporation, hence the higher critical water input value needed to generate significant quickflow. However, this hypothesis is difficult to verify at the event scale. When storage deficits were considered, input–output relationships were stronger in the high-elevation and mostly headwater sites, confirming the tight coupling between input and outputs in smaller catchments. The rainfall threshold value was correlated with the median sub-catchment area, which suggests that threshold dynamics are not influenced by the basin's total drainage area but rather by the spatial organization and topology of hydrological response units (Buttle, 2006). This is consistent with previous scaling work which revealed that streamwater mean residence time was unrelated to basin area, but rather strongly controlled by internal distributions of flowpath length and gradient or drainage density (McGuire *et al*., 2005) or by soil typology (Hrachowitz *et al*., 2009). It is, however, worth noting that the differences between controls on rain-only events and those on rain + snowmelt events might be because of the small number of sites ($n \leq 9$): slight changes in the ranking of catchments according to their threshold values for different types of events can indeed lead to significant differences in the computed Spearman rank $\text{corr}_{\text{catchment}}$ values.

How do our results compare to previous threshold studies?

Threshold types and values. Some of the runoff initiation and effective precipitation input thresholds reported here fall within the range of previously published data for rainfall-triggered events (Table IV) while others were well above this range. Most threshold values reported in the literature at the hillslope scale range from 55 mm or less (Whipkey, 1965; Mosley, 1979; Tani, 1997; Buttle *et al*., 2004; Uchida *et al*., 2005, 2006; Tromp-Van Meerveld and McDonnell, 2006a), whereas catchment-scale studies (Graham and McDonnell, 2010; Penna *et al*., 2011) have identified input rainfall threshold values that cover a wider range than hillslope studies (e.g. 23 mm in a 1.9 km^2 headwater catchment in the Italian Alps; 8.5 mm in a 3.8 ha catchment at Maimai; 56+ mm at one of the North-Watch sites, HJ Andrews). Graham and McDonnell (2010) found that the rainfall threshold could vary from 0 to 83 mm at HJ Andrews depending on antecedent drainage within two nested 9 to 101.3 ha sub-watersheds. In previously published studies, thresholds for hillslope runoff initiation have been found to be greater than runoff initiation thresholds for the catchments these hillslopes reside in. This is likely because of the fact that additional geomorphic features at the catchment scale (i.e. riparian zones) are closely linked to the channel and show more immediate connection to catchment flow response. McGlynn and McDonnell (2003) showed strong hysteresis in streamflow response to storm rainfall, whereby rising groundwater levels in riparian zones occur before the rising limb of the storm hydrograph and the threshold-like hillslope response precedes the falling limb of the storm hydrograph. Thus, larger catchment-scale runoff initiation thresholds can also be attributed to the variable buffering potential of the riparian zone (McGlynn and McDonnell, 2003). Similarly, Tetzlaff *et al*. (2014) found that a peatland riparian zone in a sub-catchment of the Girnock provided runoff responses to small events (>3 mm), but only in larger events (>30 mm) did surrounding hillslopes connect and produce a nonlinear increased runoff response. These findings are broadly consistent with those of the present study.

Shapes of nonlinear input–output relationships. Previous studies have shown different shapes of nonlinear hydrological behaviours such as the hockey stick (e.g. Weiler *et al*., 2005; Tromp-Van Meerveld and McDonnell, 2006a; Detty and McGuire, 2010), the Heaviside or step function (e.g. James and Roulet, 2007) or the sigmoid function (e.g. Zehe *et al*., 2007); nevertheless, reasons behind those different shapes have not been explained. At the hillslope scale, input–output relations from a range of hillslopes were shown to fit the hockey stick shape with the only nuance that the slope of the relationship after the threshold varied among the sites (Weiler *et al*., 2005). In this paper, a single conceptualization of nonlinear behaviour (the hockey stick) was applied to all nine catchments for the sake of simplicity and site comparison and not necessarily because similarities in underlying processes, connectivity structure between landscape units or storage capacities were assumed across the nine sites (following the logic of Lehmann *et al*., 2007). Surprisingly, however, when strong nonlinear input–output relationships were present in the data, the hockey stick conceptualization seemed appropriate to portray the catchments' hydrological behaviour (Figure 4). When thresholds were identifiable, the R^2 (that is correlated to the slope) of the input–output relationship above the threshold was specific to each catchment, as found by Weiler *et al*. (2005) at the hillslope scale. As for the input–output patterns labelled as 'unclear' (Table IV), it was not possible to say from a visual assessment alone whether other types of nonlinear functions would have fitted the data better and led to the identification of hydrologic thresholds.

Threshold identification methodology. The largest methodological challenge in this study was the visual identification of nonlinear behaviours from scatter plots, namely the identification of the critical input value as the first point where the input–output 'curve' departs from zero or a given minimum level in Figures 2–5. While previous hydrologic studies showed rather clear input–output threshold relationships because of less data points or clearer dynamics at the hillslope scale, such was not the case here where we identified the clearest inflection point in each scatter plot – when it existed. On most plots in Figures 2–5, however, data points tended to cluster in a band around the inflection point, thus suggesting a range of possible threshold values. For each catchment, the thresholds reported in Table IV were the highest among the range of possible values. While this methodological choice likely led to a bias towards higher threshold values, it was assumed that this bias would be consistent across all sites and would not change the ranking of the catchments when sorted according to ascending threshold values.

Detty and McGuire (2010), who worked at one of the North-Watch sites (Hubbard Brook), implied that well-identified precipitation input thresholds should be associated with an almost zero slope below the threshold and an R^2 value close to 1 above the threshold. One can, however, hypothesize that in the context of large and complex catchments, process-specific thresholds likely combine to determine the overall switching 'on and off' of runoff contributing zones at the catchment scale, and this superimposition of process dynamics could lead to piecewise (or hybrid) input–output functions. This is especially probable for cold-region landscapes where snowmelt can significantly increase the amount of active source areas and water inputs to the stream through a cascade of soil moisture storage thresholds, snowpack water storage thresholds and radiation intensity thresholds that influence the rate of ground thaw. Such a superposition of storage and intensity thresholds would make any visual assessment of precipitation-runoff response impossible and rather require a mathematically based detection method (Lintz *et al*., 2011). Here, it is suggested that in the case of complex cold region catchments in particular, nonlinear and domain-dependent mathematical functions should be examined with regards to their potential to account for multiple storage and/or intensity thresholds driving the system over different possible ranges of inputs.

CONCLUSION

The novel contributions of this study were to (i) shift the focus from single humid temperate catchments to a range of contrasting mid-latitude to high-latitude catchments, (ii) test for the existence of runoff initiation and effective precipitation thresholds in rainfall-driven *versus* snowmelt-driven conditions, and (iii) investigate physiographic and hydroclimatic drivers behind precipitation-runoff response. The work could be useful to up-scale or down-scale threshold values based on drainage basin properties and hydroclimatic properties. Storm amount critical values were quantified, and out of the nine catchments investigated, one was characterized by a linear input–output behaviour while the others were mainly associated with nonlinear behaviours. The consideration of antecedent storage deficit slightly improved the ability to characterize the different rainfall-runoff catchment dynamics. For rainfall-triggered events, catchment hydroclimatic or physical characteristics such as the median flow path distance to the stream, the mean annual air temperature or the median sub-catchment area were strong predictors of either the strength of the hydrological input–output relationship or the actual runoff initiation or effective precipitation threshold value identified for each site. The characterization of snowmelt-runoff catchment dynamics was more difficult, however, suggesting that the sole focus on input magnitude thresholds (i.e. storage thresholds) might be insufficient to understand catchment behaviour when snowmelt constitutes a large portion of the water input. Further studies are therefore needed to investigate the relative effects of storage and intensity thresholds in northern regions where energy dynamics are critical in runoff generation.

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