Controls on snowmelt water mean transit times in northern boreal catchments

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Abstract:

Catchment-scale transit times for water are increasingly being recognized as an important control on geochemical processes. In this study, snowmelt water mean transit times (MTTs) were estimated for the 15 Krycklan research catchments in northern boreal Sweden. The snowmelt water MTTs were assumed to be representative of the catchment-scale hydrologic response during the spring thaw period and, as such, may be considered to be a component of the catchment's overall MTT. These snowmelt water MTTs were empirically related to catchment characteristics and landscape structure represented by using different indices of soil cover, topography and catchment similarity. Mire wetlands were shown to be significantly correlated to snowmelt MTTs for the studied catchments. In these wetlands, shallow ice layers form that have been shown to serve as impervious boundaries to vertical infiltration during snowmelt periods and, thus, alter the flow pathways of water in the landscape. Using a simple thought experiment, we could estimate the potential effect of thawing of ice layers on snowmelt hydrologic response using the empirical relationship between landscape structure (represented using a catchment-scale Pe number) and hydrologic response. The result of this thought experiment was that there could be a potential increase of 20–45% in catchment snowmelt water MTTs for the Krycklan experimental catchments. It is therefore possible that climatic changes present competing influences on the hydrologic response of northern boreal catchments that need to be considered. For example, MTTs may tend to decrease during some times of the year due to an acceleration in the hydrologic cycle, while they tend to increase MTTs during other times of the year due to shifts in hydrologic flow pathways. The balance between the competing influences on a catchment's MTT has consequences on climatic feedbacks as it could influence hydrological and biogeochemical cycles at the catchment scale for northern latitude boreal catchments. Copyright © 2010 John Wiley & Sons, Ltd.

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INTRODUCTION

The hydrologic response of a catchment is typically considered to be forced by the climate (e.g. precipitation and solar radiation) and controlled by the structure of the catchment (e.g. geology and topography). Much hydrologic research, therefore, focuses on connecting catchment-scale hydrologic response to landscape controls with mean transit time (MTT) as an indicator of catchment-scale hydrologic response. Such connections might form the basis for predictive tools of hydrological catchment behaviour for ungauged basins (McDonnell *et al.*, 2007).

Estimation of the transit-time distribution and the associated MTT at the catchment scale using inverse techniques such as the lumped parameter convolution approach (i.e. McGuire and McDonnell, 2006) remain popular despite several shortcomings. While originally

developed for quasi-steady-state groundwater systems, this time-invariant approach of linear superposition of system responses has been useful in many surface water studies (Kirchner *et al.*, 2001; McGuire *et al.*, 2005; Lyon *et al.*, 2008; Hrachowitz *et al.*, 2009a). Variable flow approaches have been suggested (e.g. Niemi, 1977; Yurtsever and Payne, 1986; Rodhe *et al.*, 1996) but have seen limited acceptance because of their mathematical complexity. Practical limitations to their application in multiple, nested catchment systems due to increased data requirements (i.e. observation of both tracer and discharge at several locations) could also exist. In addition, when the variable part of a flow system is small compared to the system as a whole, the information attainable from adopting a variable flow approach is similar to that under quasi-steady flow approximation (Maloszewski and Zuber, 1993). There are also difficulties associated with characterizing catchment inputs for a lumped parameter convolution approach to determine transit-time distributions and MTTs as rainfall or snowmelt is often highly variable in space and time for

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tracer composition and amount (McGuire and McDonnell, 2006). All these factors lead to some uncertainties associated with MTTs estimated using lumped parameter convolution approaches. Regardless, the lumped parameter approach offers a simple methodology to investigate how water moves through the landscape by convoluting an observable albeit simplified input signal into an observed output signal.

MTTs for small catchments have been described to be controlled by two main factors: topography and typology. These are the first two Ts of the Buttle's (2006) T³ template. The third T, topology, deals primarily with stream or channel network configurations that are often assumed negligible (for simplicity) in small-catchment systems or with the connectivity across landscape units. McGuire *et al.* (2005) at HJ Andrews (Western Cascades, USA) and McGlynn *et al.* (2003) in Maimai (New Zealand) showed the importance of topographic control. In contrast, Soulsby *et al.* (2006a,b) and Tetzlaff *et al.* (2009a) found that in recently glaciated landscapes such as in Scotland, soil cover and hydrological characteristics (typology) are a more important control on catchment-scale MTTs. These two controls might be related through geomorphology and the evolution of the landscape (e.g. topography leads to soil formation which, in turn, influences topography) at long time scales. This has led recently to more holistic approaches to catchment hydrology such as Buttle's T³ template (Buttle, 2006), which recognizes that all components of a natural system (hydrology, ecology, topography, etc.) develop in concert (Troch *et al.*, 2008). Typically, the co-evolution of topography and soils as a control on catchment response occurs over such long (i.e. geologic) time scales that it is considered static over the time frame of human observation (of which catchment-scale studies tend to be limited). While this is certainly true for most warm and temperate climates, it does not necessarily hold in colder regions.

In cold regions, ice formation in soils influences the distribution of hydrologic pathways (Woo *et al.*, 2008). Such ice layers may be permanent (i.e. permafrost) or more transient such that their position (existence) fluctuates seasonally and annually. For example, in arctic and subarctic systems, ice layers at the interface of the organic and mineral soils have often been cited as the main cause of lateral runoff (Kane *et al.*, 1981; Roulet and Woo, 1988; McNamara *et al.*, 1997), with much research emphasizing their role in water storage and restriction of transmittance properties (Santeford, 1979; Slaughter and Kane, 1979; Hinzman *et al.*, 1993; McNamara *et al.*, 1998). Seasonal fluctuations in the active layer for northern systems has been observed to directly influence the hydrologic response at the hillslope and catchment scales (Carey and Woo, 2001; Yamazaki *et al.*, 2006; Woo *et al.*, 2008). In addition, a long-term change in permafrost influences the hydrologic response. Recently, Lyon *et al.* (2009) and Lyon and Destouni (2009) used long records of observed streamflow and recession flow analysis to estimate catchment-scale changes in permafrost position.

This technique connected changes in hydrologic response to changes in catchment structure.

In boreal systems, soil ice in mire wetlands has been shown to influence the pathways water takes in the landscape (e.g. Spence and Woo, 2006). Specifically, Laudon *et al.* (2007) observed that the proportion of wetland and median catchment area influenced the runoff generation mechanisms in several small catchments located in boreal northern Sweden. As the formation of these ice layers is sensitive to climatic variability and change, it reasons that climate change may influence catchment MTT, particularly during spring thawing in boreal systems not only through changes in forcing but also through changes in structure. On the basis of this previous work, we consider the role of catchment characteristics (e.g. topographic and landscape) and structure in relation to the hydrologic response for these catchments during spring melt periods. The main goal of this study was to estimate the MTTs for snowmelt water moving through the 15 Krycklan catchments located in northern boreal Sweden. We also investigated empirical links between several topographic and landscape factors of the 15 catchments and the snowmelt MTTs estimated from stable water isotope sampling. In addition, we developed a simple empirical model based on a catchment-scale similarity parameter. This empirical model allowed us to formulate a simple thought experiment to speculate about the potential effects of climate change on wetland soil ice layers and the influence this could have on the hydrologic response of these northern boreal catchments during spring melt. Primarily, we test the hypothesis that effectively deeper wetlands during spring thaw could lead to increased snowmelt water MTTs at the catchment scale due to deeper flow pathways that, in effect, dampen the system response of conservative solutes.

STUDY AREA

The Krycklan Catchment Study contains 15 nested research catchments within the Vindeln Experimental Forests (64°140'N, 10°460'E) that are approximately 50 km northwest of Umeå, Sweden (Figure 1). These 15 boreal catchments range in size from 0.03 to 67 km². This region is climatically typified by short summers and long winters. Snow covers the ground on average for 171 days, from the end of October to the beginning of May (Ottosson-Löfvenius *et al.*, 2003). The mean annual precipitation and temperature are 646 mm and +1.8 °C respectively, with about 50% of the annual precipitation falling as snow.

The upland parts of the main catchment are mainly forested with Norway spruce (*Picea abies*) in low-lying areas and Scots pine (*Pinus sylvestris*) in upslope areas. Large patches of mire wetlands predominantly in the upper part of the main catchment are also present. In the lower regions, Norway spruce and Scots pine are also the dominant tree species, but deciduous trees and shrubs are more common along the stream channels.

Figure 1. Site map showing the location of the Krycklan Catchment Study in northern Sweden and the outlets of the 15 Krycklan catchments used in this study. The largest catchment outlet (site 16) is located at 64°12'N and 19°52'E. Lakes are in black, mire wetlands are in grey and silt soils are indicated with cross hatching

Small areas of agricultural fields are found in the lower part of the catchment. Geologically, these catchments are located on the Fennoscandian shield and overlay gneissic bedrock (Buffam *et al.*, 2007). Glacial tills in the upper portion of the main catchment give way to deeper sorted sediments towards the catchment outlet (Figure 1). Subsurface pathways dominate the forested sites with overland flow rarely occurring due to the high infiltration capacity of the till soils (Bishop *et al.*, 1990; Laudon *et al.*, 2004). Well-developed iron-podzol soils are common and, in the lower reaches, larger streams have incised channels carving through fine-grained floodplain sediments (Buffam *et al.*, 2007).

METHODS AND MATERIALS

Time series of isotopic data

The present study makes use of data collected in conjunction with previous and on-going field campaigns spanning the last 20 years at the research catchments as part of the Krycklan Catchment Study. The details of the field techniques and sampling strategies used in these various studies are provided to a large extent in Bishop *et al.* (1990); Ågren *et al.* (2007); Laudon *et al.* (2007) and Köhler *et al.* (2008). In the current study, we use time series of $\delta^{18}\text{O}$ observed in snowmelt and streamflow water for the 15 nested Krycklan catchments. Analysis of collected water samples was performed using a GASBench II (Finnigan MAT) connected to a Delta plus mass spectrometer (Finnigan MAT). Data was normalized so that the difference between Standard Light Antarctic Precipitation (SLAP) and Standard Mean Ocean Water (SMOW) was -55.5‰ (Coplen, 1995). The accuracy

was always better than 0.2‰ based on in-house quality-control measurements. These time series of $\delta^{18}\text{O}$ values for the input (snowmelt) and output (streamflow) signal from 15 nested catchments under similar geologic and climatic settings provide a unique dataset to observe snowmelt water MTTs.

The output time series is based on 1 year of streamflow $\delta^{18}\text{O}$ values for all 15 catchments for the year 2004 (Figure 2). Frequent sampling was conducted during snowmelt periods (one sample collected at each catchment outlet about every third day in April and May) for 2004, while monthly sampling was used during the remainder of the year. For each catchment, there was a clear response in streamflow $\delta^{18}\text{O}$ values during the spring melt period (Table I) indicated by a significant difference between the maximum and minimum observed streamflow $\delta^{18}\text{O}$ values.

Two input time series are considered on the basis of a combination of streamflow and snowmelt $\delta^{18}\text{O}$ values available for the 2004 sampling season (see Laudon *et al.*, 2007 for details). Note that, currently, no rainfall $\delta^{18}\text{O}$ values are available during the 2004 snow-free period. This adds some uncertainty to the representation of input water to the catchments after the snowmelt period. There was relatively small spatial variability but considerable temporal variability in snowmelt water $\delta^{18}\text{O}$ values (Laudon *et al.*, 2007). Observed snowmelt water $\delta^{18}\text{O}$ values in the first melt water leaving the snow pack were -18.1 , -18.3 and -17.3‰ in open field, open canopy and closed canopy respectively (Laudon *et al.*, 2007). At the end of the melt season, the corresponding values were -15.7 , -15.8 and -15.2‰ , suggesting a large fractionation during snow melt (Laudon *et al.*, 2007). Laudon *et al.* (2007) report average snowmelt $\delta^{18}\text{O}$

Figure 2. Snowmelt water input (solid grey line) and streamflow water output (dots) observed for each of the 15 Krycklan catchments along with the best-fitting lumped parameter convolution model predicted output (solid black line) from 1 January 2004 through 31 December 2004. Input and modelled output shown only for representing snow melt water as a constant isotopic value

values from volume-weighted snowmelt water of -16.1 , -16.0 and -15.9‰ for open field snow lysimeters, open canopy snow lysimeters and closed canopy snow lysimeters, respectively, over the entire 20 days of the snowmelt season (9 April 2004 through 29 April 2004). For simplicity in this study, we consider two different snowmelt water isotopic scenarios. The first assumes that snowmelt water has a constant isotopic value of -16.0‰ for all of the 15 Krycklan catchments over the 20 days of observed snowmelt. The second allows for a linear enrichment of snow melt water with respect to $\delta^{18}\text{O}$ values over the melt period. Thus, snow melt water starts with an $\delta^{18}\text{O}$ value of -17.9‰ , representing the average of the first melt water leaving the snow pack observed by Laudon *et al.* (2007) and enriches linearly to a value of -15.6‰ representing the average of the last

observed melt water. These snowmelt $\delta^{18}\text{O}$ values may be considered as pulses of input snowmelt water to the Krycklan catchments.

To trace these pulses of water through each catchment, we superimpose these signals onto an isotopic signal more representative of non-melt-period streamflow water before and after spring melt. To represent the non-melt period before the onset of spring melt for each catchment, we take the average of the first three streamflow $\delta^{18}\text{O}$ values for each catchment. The first three samples cover a time period of roughly 100 days for each catchment. To represent the non-melt period after the cessation of spring melt for each catchment, we take the average of the last three streamflow $\delta^{18}\text{O}$ values observed for each catchment. There is a time lag between the end of the snowmelt period and the first of these three

Table I. Observed range in streamflow $\delta^{18}\text{O}$ values and the estimated MTTs from the lump parameter convolution using both a constant isotopic value for snowmelt water and a linear enrichment over the melt period

ID	Maximum observed $\delta^{18}\text{O}$	Minimum observed $\delta^{18}\text{O}$	Constant snowmelt isotopic value			Linear enrichment snowmelt isotopic value		
			MTT (days)	5th/95th percentiles (days)	NSE	MTT (days)	5th/95th percentiles (days)	NSE
Site 1	-12.8	-14.0	67 (60–75)	5/201	0.83	91 (80–104)	5/273	0.77
Site 2	-12.9	-13.8	133 (110–167)	7/398	0.48	180 (148–230)	9/539	0.43
Site 3	-13.1	-15.4	25 (20–31)	1/75	0.81	40 (33–50)	2/120	0.76
Site 4	-12.7	-15.5	10 (9–12)	1/30	0.84	19 (16–23)	1/57	0.79
Site 5	-10.6	-13.6	31 (28–35)	2/93	0.83	38 (35–43)	2/114	0.82
Site 6	-11.9	-13.7	51 (44–59)	3/153	0.68	65 (57–75)	3/195	0.68
Site 7	-12.9	-14.1	67 (54–88)	3/201	0.55	93 (74–121)	5/279	0.53
Site 8	-13.0	-14.2	57 (51–64)	3/171	0.85	81 (72–91)	4/243	0.81
Site 9	-12.6	-13.9	45 (39–54)	2/135	0.69	62 (54–72)	3/186	0.70
Site 10	-13.1	-14.7	42 (33–56)	2/126	0.67	64 (51–84)	3/192	0.64
Site 12	-13.1	-14.3	61 (49–80)	3/183	0.59	88 (70–115)	5/264	0.55
Site 13	-12.8	-14.1	45 (38–54)	2/135	0.68	62 (54–73)	3/186	0.72
Site 14	-12.9	-14.9	59 (1–106)	3/177	0.38	84 (57–145)	4/252	0.37
Site 15	-12.7	-14.0	43 (37–49)	2/129	0.77	58 (52–66)	3/174	0.78
Site 16	-12.8	-14.5	81 (54–140)	4/243	0.38	111 (76–193)	6/333	0.35

The values in parentheses show the range of MTTs obtained increasing in the minimized least squares statistic by 5% as a metric objective function convergence. The corresponding 5th/95th percentiles of the exponential distributions and the NSE for the 15 Krycklan catchments are also shown.

streamflow $\delta^{18}\text{O}$ values for each catchment of about 160 days. The resulting input time series of $\delta^{18}\text{O}$ values resembles a unique saw-tooth pattern for each of the 15 Krycklan catchments (Figure 2). This methodology for representing the input signal is similar to that applied by Lyon *et al.* (2008) for estimating an event-scale transit-time distribution in response to an extreme rainfall event. Our current method differs from Lyon *et al.* (2008) in that the pre-melt signal is different than that used to represent the post-melt signal; thus, we do not assume that there is a cyclic pattern where the input signal at the beginning of the year matches the signal at the end of the year (at least at the scale of 1 year) intrinsic to the isotopic inputs to these catchments. As rainfall occurs during the post-melt period, there is likely an influence of this rain water's isotopic composition on the input signal to the catchments. Without direct measures of this rain water isotopic composition, however, we are unable to directly represent its influence on the input signal. By using the last three stream samples collected a long time after the cessation to snowmelt (here, 160 days after the end of snow melt to the end of the year), we can approximate the influence of this water on the input signal. This, of course, adds to the uncertainty associated with the absolute MTTs estimated from these composite input signals.

Estimating snowmelt water MTT

Snowmelt water MTTs were modelled using the lumped parameter convolution approach. See McGuire and McDonnell (2006) for a recent review of the methodology. The lumped parameter convolution approach uses a weighting or kernel function, $g(\tau)$, to describe the transport of a conservative tracer through a catchment. Using this approach, an output signal (streamflow in this study) at any time, $\gamma_{\text{out}}(t)$, consists of the input signal (combinations of snowmelt streamflow in this study) of the

tracer, $\gamma_{\text{in}}(t - \tau)$, applied uniformly over the catchment in the past ($t - \tau$), which becomes lagged according to its transit-time distribution, $g(\tau)$ (Barnes and Bonell, 1996; Kirchner *et al.*, 2000):

$$\gamma_{\text{out}}(t) = \int_0^\infty g(\tau) \gamma_{\text{in}}(t - \tau) d\tau \quad (1)$$

where τ are the lag times between input and output signals. To limit the amount of parameter calibration in applying the lumped parameter approach, we used a mathematical function to express the transit-time distribution in this study. Several distributions are possible, but we have restricted ourselves to the widely used exponential distribution as it is parsimonious in the number of fitted parameters. Following Maloszewski and Zuber (1982), this exponential transit-time distribution, $g(\tau)$, has the form:

$$g(\tau) = \frac{1}{\tau_m} \exp\left(-\frac{\tau}{\tau_m}\right) \quad (2)$$

where τ_m denotes the first moment of the transit-time distribution or the MTT of the transit-time distribution. The exponential transit-time distribution describes a catchment with flow times that are distributed exponentially, including pathways with very short transit times (McGuire and McDonnell, 2006), and represent the apparent behaviour of a well-mixed linear reservoir (Maloszewski and Zuber, 1982; Rodhe *et al.*, 1996). To fit the exponential transit-time distribution parameter, τ_m in Equation (1) was adjusted iteratively using the input signal (snowmelt) described in the previous section to minimize the following least squares statistic (Maloszewski and Zuber, 1996; McGuire *et al.*, 2002):

$$\sigma = \left[\sum_{i=1}^n (O_i - X_i)^2 \right]^{1/2} \quad (3)$$

where O_i are observed output (streamflow) $\delta^{18}\text{O}$ values and X_i are the model simulated $\delta^{18}\text{O}$ values with n being the number of observations. The τ_m that minimized Equation (3) for each catchment was assumed to provide the best fit and was adopted as the snowmelt water MTT for that catchment. We report the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and the corresponding 5th/95th percentiles of the exponential distributions for the resulting best fit (Table I) as a metric of goodness of fit. In addition, we consider the uncertainty associated with the MTTs by observing the convergence of the objective function (namely, Equation (3)). By convergence, we mean how quickly the least squares statistic approaches a minimum value. To do this, we consider the influence of a 5% increase in the minimized least squares statistic and report the corresponding range of estimated snowmelt water MTTs. This gives in a narrower range of estimated MTT for the catchments with more convergent objective functions.

It should be noted that in this formulation the lumped parameter convolution is expressed in clock-time and not flow-corrected time (e.g., Rodhe et al., 1996) or what could be considered explicitly as a nonsteady-state approach (e.g., Neimi, 1977). We were limited (practically) in this respect as discharge during the period considered in this study was available for only 1 of the 15 Krycklan catchments. Using flow-corrected time based on one single discharge time series might change the estimated absolute MTT values, but it likely would have little influence on the relative differences between catchments MTTs. Here, we let the simplicity of the lumped parameter approach and the uniqueness of the dataset that is available for comparisons among the catchments outweigh the uncertainty due to assumptions regarding absolute transit-time estimates.

Catchment characteristics and structure

Topographic analysis. For topographic factors in this study (Table II), we take the suite of indices considered by Tetzlaff *et al.* (2009b). As there are many possible indices, we consider this a sufficient cross section of what could be considered ‘basic’ indices. A raster digital elevations model (DEM) with a 10-m resolution was used for analysis of topographic characteristics. A stream network was generated from the DEM based on the accumulated upslope area and assuming a threshold area of 5 ha for stream initiation. Using this stream network, the median catchment area was computed as the median of the local catchment areas of all stream pixels upstream of the catchment outlet. Each pixel was linked to the stream pixel to which it drained by assuming that the flow path follows the surface topography using a multi-directional flow algorithm (Seibert and McGlynn, 2007). On the basis of this flow path, five indices were computed for each pixel: the elevation above the stream, the distance from the stream, the average gradient along the flow pathway to the stream and the ratio of the flow path length and gradients, which is often considered a proxy for travel times, summed along the entire flow

Table II. Catchment characteristics considered in this study for each of the 15 Krycklan research catchments

Factor	Units	ID														
		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 12	Site 13	Site 14	Site 15	Site 16
Upslope area	km ²	0.6	0.1	0.0	0.2	0.8	1.3	0.5	2.5	3.1	3.2	5.7	7.3	12.6	19.7	66.8
Median catchment area	ha	22	10	16	16	9	21	25	42	31	45	46	41	22	24	23
Elevation above stream	m	15	16	10	5	4	6	5	13	7	7	8	8	10	10	10
Distance from stream	m	243	226	265	208	206	177	127	224	167	186	193	190	184	177	181
Average gradient	—	0.06	0.07	0.04	0.02	0.02	0.03	0.04	0.05	0.04	0.04	0.05	0.04	0.07	0.06	0.06
Ratio of flow path length and gradients	m	3836	3821	14 567	27 587	25 301	12 548	5093	5370	6232	7945	6150	6140	5405	5823	4980
Downslope index	—	0.06	0.07	0.07	0.03	0.03	0.04	0.04	0.06	0.05	0.05	0.05	0.05	0.08	0.07	0.07
Topographic wetness index	Ln (m)	9.6	8.9	9.0	8.8	9.1	9.1	8.9	9.1	9.1	9.1	9.3	9.3	8.9	8.8	8.9
Percentage wetland area	%	2.7	1.3	45.3	50.4	36.7	25.6	17.3	12.2	14.6	25.9	17.4	11.1	5.7	13.7	8.6
Average soil depth (3/10 m)	m	2.9	3.0	1.6	1.5	1.9	2.2	2.5	2.6	2.9	2.2	2.7	3.6	4.9	2.7	4.4
Average soil depth (1/5 m)	m	1.0	1.0	0.6	0.5	0.6	0.7	0.8	0.9	1.1	0.7	0.9	1.4	2.1	0.9	1.9
Average soil depth (0.5/1 m)	m	0.5	0.5	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.6	0.4	0.6
Catchment Pe number (3/10 m)	—	27	19	27	59	65	44	31	33	30	35	30	27	33	35	30
Catchment Pe number (1/5 m)	—	81	58	94	142	185	124	81	98	84	103	86	75	81	95	77
Catchment Pe number (0.5/1 m)	—	161	116	191	264	359	245	155	193	173	204	179	157	181	203	177

pathway. In addition, the downslope index (Hjerdt *et al.*, 2004) was defined as the gradient towards the closest point, which is at least 5 m (in altitude) below the pixel in question. The upslope area and slope were combined into the topographic wetness index ($\ln[a/\tan(\beta)]$) similar to Beven and Kirkby (1979), where a is the upslope area per unit contour length and $\tan(\beta)$ is the local slope with the difference that here $\tan(\beta)$ was defined using the downslope index (Hjerdt *et al.*, 2004). For each of these indices considered, catchment-wide median values were computed to represent each of the catchments. Interested readers are referred to Tetzlaff *et al.* (2009b) for complete methodological procedures.

Landscape analysis. In addition to these topographic factors, we considered other landscape factors (Table II) based on experience within the region. Motivated by the work of Laudon *et al.* (2007), the percentage of area in each catchment covered by mire wetland was determined. Using the local soil classification map, the average soil depth for each of the catchments was estimated. This factor is included because soils and soil storage have been seen as dominating controls on catchment MTTs in regions with similar geomorphic settings (e.g. Hrachowitz *et al.*, 2009a). Soil depth is a difficult property to estimate as it requires subsurface estimations as opposed to the previous measures that can be estimated from DEM or map analysis. As a high-resolution detailed mapping of soil depth was not available, we considered three potential combinations of soil depths for each of the two dominant soil classes (tills and sediments) based on field observations. For the thinner till soils located in upland regions dominated by unsorted till and for the deeper low-lying sediments, these potential soil depth combinations were considered as 3/10, 1/5, 0.5/1 m for the till/sediment soil depths, respectively. These three combinations are assumed to cover the range from the deepest possible soil profiles—where tills are 3 m deep and sediments are 10 m deep—to the shallowest possible soil profiles where tills and sediments are 0.5 and 1 m deep respectively. Finally, we adopt very shallow soil depths (1 cm) in the mire wetlands based on winter and spring thaw field observations (Laudon *et al.*, 2007) to simulate the influence of impervious ice layers that currently form during winter and snowmelt periods. These wetland ice layers are persistent during the spring thaw period of the year and heavily influence the resulting hydrologic response of the landscape. The soil depth for each catchment was taken as an area-weighted average of the depths of soils in the catchment.

Similarity analysis. By ‘similarity’, we mean a quantifiable parameter capable of discerning how similar or dissimilar catchments are with respect to their hydrological response (Wagener *et al.*, 2007). While many potential similarity parameters are available to investigate structure (e.g. Sivapalan *et al.*, 1987; Harman and Sivapalan, 2009), we adopt a catchment Péclet number

(Pe) (Lyon and Troch, 2009) number based on the hillslope Pe number (Berne *et al.*, 2005; Lyon and Troch, 2007). Here, we mean structure in terms of both geomorphology (spatial variability of slope, aspect and shape of the land surface) and pedology (spatial variability of soil depth, soil structure and hydraulic properties). This subsurface flow similarity parameter should provide an adequate representation of the underlying physics (to a first-order approximation where hillslopes are characterized by relatively shallow soils underlain by impermeable bedrock, streamlines are essentially parallel to the impervious bedrock, storage in the unsaturated zone has a negligible delaying effect on subsurface flow response and there is a general absence of overland flow) behind the hydrologic responses for catchments in the size range and geomorphologic setting considered in this study.

The dimensionless Péclet number (Pe) is a hillslope-scale similarity parameter that defines the ratio of the diffusive flow scale and advective flow time scale in an unconfined sloping aquifer (Brutsaert, 1994; Troch *et al.*, 2004):

$$Pe = \left(\frac{L}{2pD} \right) \tan \alpha - \left(\frac{a_c L}{2} \right) \quad (4)$$

where L is the hillslope length, α is the hillslope angle, D is soil depth, p is a linearization parameter and a_c is the hillslope plan shape convergence rate.

To estimate Pe numbers at a catchment-scale for each of the 15 Krycklan research catchments (Table II), we used an area-weighted average of the hillslope Pe numbers (Equation (4)) of the individual hillslopes making up each catchment (Lyon and Troch, 2009):

$$\text{catchment Pe} = \frac{\sum_{i=1}^n A_{h_i} Pe_i}{\sum_{i=1}^n A_{h_i}} \quad (5)$$

where A_h is the individual hillslope area for each of the n hillslopes in a given catchment. Lyon and Troch (2009) demonstrated that using an area-weighted average of the hillslope Pe numbers to generate a catchment-scale Pe number agreed with the hydrologic response (represented using the moments of a characteristic response) as well as using a storage volume-weighted value when considering Pe numbers of the scale found in real-world landscapes.

Hillslopes were delineated and defined using the techniques given by Bogaart and Troch (2006) and Lyon and Troch (2007). The individual hillslope area (A_h), angle (α) and length (L) were determined using topographic analysis on the DEM. The hillslope convergence rate (a_c) for each individual hillslope was determined assuming exponential or uniform width functions (Troch *et al.*, 2003; Berne *et al.*, 2005; Lyon and Troch, 2007). The linearization parameter (p) was defined using a theoretical value of 0.30 (Brutsaert, 1994). The soil depth (D) for each hillslope was taken as an area-weighted average of the soils in the hillslope determined from a local soil classification

map with three potential soil depth combinations considered at 3/10, 1/5, 0.5/1 m for the till/sediment soil depths, respectively, while very shallow soil depths (1 cm) were taken in the mire wetlands based on winter and spring thaw observations (Laudon *et al.*, 2007). This approach creates three sets of catchment Pe numbers for each of the 15 Krycklan catchments based on variations in assumed soil depths.

RESULTS

Isotope time series and catchment MTT estimates

Time series of observed $\delta^{18}\text{O}$ values provide a characterization of the input and output signals to the Krycklan research catchments (Figure 2). A previous work shows that short-term data can lead to highly variable estimates of MTTs when the observation record is short relative to the length of transit times in the catchment (Tetzlaff *et al.*, 2007; Hrachowitz *et al.*, 2009b). In this study, we are estimating the snowmelt water MTTs for a given year of observations. We expect the estimated snowmelt water MTT to vary between years depending on many factors (e.g. amount of snowfall, timing and duration of melt) and do not assume that the snowmelt water MTTs empirical estimated here are time-invariant such that they are constant across all snowmelt seasons. The purpose of this study is to observe relative differences between catchments rather than estimating absolute MTT.

The snowmelt water MTTs range from 10 days for site 4 to 133 days for site 2, adopting a constant isotopic value of -16.0‰ to represent snowmelt water (Table I). Using this input signal, the average snowmelt water MTT for the Krycklan catchments is 54 days with a standard deviation of 28 days. The NSE for the simulated output time series using exponential transit-time functions range from 0.38 to 0.85 with an average of 0.67 for the 15 Krycklan catchments. The snowmelt water MTTs range from 19 days for site 4 to 180 days for site 2, adopting an enrichment in the snowmelt isotopic value increasing linearly from -17.9‰ representing the average of the first melt water leaving the snow pack to -15.6‰ representing the average of the last melt water leaving the snow pack (Table I). Using this input signal, the average snowmelt water MTT for the Krycklan catchments is 76 days with a standard deviation of 38 days. The NSE for the simulated output time series using exponential transit time functions range from 0.35 to 0.82 with an average of 0.65 for the 15 Krycklan catchments. The ranges of MTTs obtained by increasing the minimized least squares statistic by 5% shows that the convergence of the objective function varies across the 15 Krycklan catchments. This is regardless of the input signal used.

For both input signals, the sites with the highest MTT (site 2) and the lowest MTT (site 4) are located within about 1 km and the catchments are similar with regards to upslope area. Despite this proximity in space and similarity in size, the range of snowmelt water MTTs covers 1 order of magnitude. The main difference

between sites 2 and 4 is the landscape characteristics (Table II). In addition, site 4 has a larger percentage covered by mire wetlands than site 2. Site 4 has one of the largest percentage areas covered by mire wetlands of any of the 15 Krycklan catchments. Site 2 has a deeper soil profile (on average) based on the estimate used in this study than site 4.

There is a difference in estimated MTTs due to the adoption of a constant isotopic snow melt water value versus a value that enriches linearly over the snowmelt period (Figure 3). There is an average increase of about 33% using the linear enriching isotopic signal over the constant isotopic input signal. This increase, however, maintains the relative differences between individual catchment snowmelt water MTTs. While this demonstrates some of the uncertainty associated with the absolute estimated snowmelt water MTTs due to the representation of the input signal, it shows the insensitivity in the relative differences among the catchments. As such, we adopt the MTTs estimated using the constant snow melt isotopic values for the remainder of this study as we are primarily interested in the relationship between MTTs and the landscape and not the absolute estimate of MTTs.

Empirical relations between landscape and snowmelt MTT

The 15 Krycklan catchments have a range of characteristic values (Table II). Sites draining the upper portion of the study area (e.g. sites 3, 4, 5 and 6) tend to have lower average gradients and larger percentage of their total area covered with mire wetlands. This leads to relatively high ratios of flow path length to gradient for these catchments. These low gradients are reflected by low average elevations above the stream. While these sites have somewhat low downslope indices relative to the other Krycklan sites, their catchment-average topographic wetness indices fall approximately in the middle

Figure 3. Influence of representing snow melt water as a constant isotopic value versus using a linear enrichment over the snow melt period. The slope of the line is 33%

of those reported for the other Krycklan catchments. The catchment-average estimated soil depths in this upper portion of the study area (e.g. sites 3, 4, 5 and 6) tend to be lower than those in other regions. This reflects the skewed distribution of till and sediment soils such that tills are more prevalent in the upper portion of the main catchment. Catchment Pe numbers (Table II) for all 15 Krycklan catchments vary across the study area. Considering the middle soil depth profiles (1/5 m till/sediment soil depths), for example, catchment Pe numbers for the Krycklan catchments range from 58 for site 2 to 185 for site 5 with an average of 98 for all sites. Again, the upper portion of the study area in general has similar (higher) catchment Pe numbers. This is expected as this similarity parameter contains soil depth, gradient and flow path lengths in its definition and, therefore, incorporates both topographic factors and landscape factors in its description of catchment structure.

Each of the catchment characteristics listed in Table II can be empirically related to the snowmelt water MTTs estimated for the 15 Krycklan catchments (Table III). Using linear trends, there are significant ($p < 0.02$) relationships between snowmelt MTTs and several of the characteristics. These characteristics include topographic factors (average gradient and ratio of flow path length to gradient), some landscape factors (percentage wetland area and soil depth assuming the shallowest soil profiles) and all of the catchment Pe numbers. Of these significant trends, the percentage wetland area covering the catchment has the highest coefficient of determination ($R^2 = 0.59$).

Table III. Linear regressions relating snowmelt water MTTs and all landscape factors

Factor	Linear regression	R^2
Upslope area	$\tau_m = 0.37X + 51.43$	0.05
Median catchment area	$\tau_m = -0.22X + 60.16$	0.01
Elevation above stream	$\tau_m = 5.28X + 7.03$	0.05
Distance from stream	$\tau_m = -0.02X + 58.50$	0.00
Average gradient	$\tau_m = 1333.00X - 6.45$	0.52
Ratio of flow path length and gradients	$\tau_m = -0.0024X + 77.43$	0.43
Downslope index	$\tau_m = 1010.80X - 1.60$	0.29
Topographic wetness index	$\tau_m = 2.48X + 32.01$	0.00
Percentage wetland area	$\tau_m = -1.45X + 82.31$	0.59
Average soil depth (3/10 m)	$\tau_m = 14.33X + 14.63$	0.22
Average soil depth (1/5 m)	$\tau_m = 23.11X + 31.07$	0.14
Average soil depth (0.5/1 m)	$\tau_m = 172.31X + 19.82$	0.39
Catchment Pe number (3/10 m)	$\tau_m = -1.42X + 104.62$	0.39
Catchment Pe number (1/5 m)	$\tau_m = -0.57X + 109.57$	0.40
Catchment Pe number (0.5/1.0 m)	$\tau_m = -0.31X + 116.22$	0.40

In the linear regression equations, X signifies the factor as the independent variable and τ_m is the MTT. Bold text indicates $p < 0.02$ significance.

There are positive relationships between both catchment-average gradients and average soil depths and snowmelt water MTTs. Negative relationships were found between the flow path length over gradient, percentages of mire wetland area and catchment Pe numbers and the estimated snowmelt water MTTs. In general, catchments covered to a larger extent with mire wetlands have lower (faster) snowmelt water MTTs. In addition, catchments containing low gradients and shallow soils have lower (faster) snowmelt water MTTs. Note that both average gradient and soil depth are significantly correlated (or perhaps more appropriately co-vary) with percentage wetland area. While this correlation is somewhat spurious for soil depth as the estimated catchment-average soil depths (in this study) are a function of mire wetland area, it is independent of the connection between gradients and mire wetlands.

These connections between topographic factors and landscape factors and the snowmelt water MTT are captured in the relation between catchment Pe number and the snowmelt water MTT. As a catchment has a lower Pe number (i.e. the influence of advective time scale increases), there is a corresponding increase in snowmelt water MTT. This relation shows that the catchment Pe number is properly representing the physics governing shallow subsurface flow in the Krycklan research catchments. The relative relationship between the catchment Pe numbers of the individual catchments is conserved under the different soil depth profile combinations considered. As such, even if the absolute catchment Pe numbers for the Krycklan catchments are not known explicitly, we can still use the relative relationship between the catchment Pe numbers in a similarity approach to compare the relationship between snowmelt water MTTs and catchment structure among the different catchments.

A POSSIBLE INFLUENCE OF CLIMATIC CHANGES: A THOUGHT EXPERIMENT

We can take advantage of the relationship between catchment structure and hydrologic response to present a simple thought experiment to explore how climate change can restructure catchments in ways that influence the hydrology. The empirical relationships between catchment structure and snowmelt hydrologic response (Table III) mimic a present-day scenario by assuming the soil depth in all mire wetlands during snowmelt at Krycklan to be 1 cm. This depth is similar to the observed impervious wetland ice layers for this region (Laudon *et al.*, 2007). While these ice layers are temporally dynamic in that they melt seasonally as spring thaw moves into a warmer summer period, they exhibit a strong control on flow pathways during the spring melt period of the year (Laudon *et al.*, 2007). As such, estimating catchment Pe numbers assuming wetland soil depths of 1 cm provides a method to effectively capture the first-order structural control of wetland soil ice on the snowmelt hydrological response. The empirical relationship between the catchment Pe numbers and snowmelt

water MTTs can be used to estimate the potential influence of changes in the internal catchment structure.

We can recalculate catchment Pe numbers for each catchment assuming the soil depth in the wetlands to be 30 cm deep. This could be assumed to simulate an ice-free mire wetland during snowmelt. Assuming effectively deeper wetlands, there is a corresponding decrease in catchment Pe number across catchments. Using these new catchment Pe numbers and the empirical relationships defined in Table III, we can estimate the potential change in snowmelt water MTTs for the Krycklan catchments under a scenario where no wetland ice forms. This leads to a corresponding increase in the snowmelt water MTTs ranging from 20% on average to 45% on average using 3/10 m or the 0.5/1 m till/sediment soil depths, respectively.

DISCUSSION

The snowmelt water MTTs empirically estimated for the 15 Krycklan catchments represent a specific component of the many different transit times of sources of water active at the catchment scale. As recently observed by Sayama and McDonnell (2009), there are limitations in estimating time-invariant transit-time distributions with no ability to quantify the dynamics of the distributions with flow conditions and rainfall regimes. This echoes the empirical findings of Tetzlaff *et al.* (2007) and Hrachowitz *et al.* (2009b) with respect to variations in long-term catchment MTTs. Still, it may be useful to estimate the MTTs for some source water components of the catchment-scale transit-time distribution. Dunn *et al.* (2007) highlighted this usefulness in that each specific component transit time with respect to water sources may be related to characteristic properties of a catchment. Such relations could form the basis for conceptualizations of how component MTTs may evolve in response to shifts in flow conditions and precipitation regimes. For example, subsurface ice in northern climates directly influences the distribution of hydrologic pathways in the landscape and, as such, its thawing could change component MTTs. Such thawing could be considered as a more long-term process (e.g. permafrost loss) or could occur in shorter, more discrete intervals (e.g. lack of ice layer formation in boreal wetlands).

The methodology used in this study provides an estimate of the MTTs associated with the movement of snowmelt water through the shallow subsurface. This is accomplished through characterization of the isotopic input signal such that we represent the snowmelt water uniquely from a background signature of baseflow waters. Of course, this is a simplified approach to the problem as there is likely mixing between snowmelt water and deeper flow paths which maintain this baseflow water. Uncertainty is also associated with how one represents the input signal of the snowmelt water (Figure 3). While this seems to influence the absolute MTTs estimates in this study, it does not significantly influence the

relative differences among the catchments. There are uncertainties in the absolute magnitude of the estimated snowmelt water MTTs due to simplifying assumptions made intrinsically when applying this lumped parameter convolution approach. However, the results of the lumped parameter modelling in this system seem appropriate and there is general agreement between modelled output and stream observed $\delta^{18}\text{O}$ values (Table I). This general agreement (in part) is conditioned by the incorporation of stream observations into the input signal used in the lumped parameter convolution approach. In addition, the estimated snowmelt water MTTs can be related to landscape and topographic factors such that there is agreement between the estimated MTTs and the conceptualization laid out by Laudon *et al.* (2007). This gives some additional confidence that the methodology used in this study is applicable under these snowmelt-dominated conditions.

Several of the catchment characteristics representing topographic and landscape factors investigated in this study can be related to the snowmelt MTTs for the Krycklan catchments (Table III). Laudon *et al.* (2007) demonstrated a strong connection between the wetland area in these catchments and the flow path distribution. Similar to this, this study found the strongest connection (highest R^2) for a linear relationship between snowmelt MTTs and wetland area. Catchments covered by more mire wetlands have faster snowmelt water MTTs. In addition, there is a significant ($p < 0.02$) linear relation between topographic features (primarily gradient) and the snowmelt water MTTs. Counter to the typical topographic-driven controls on MTTs (e.g. McGuire *et al.*, 2005), in this boreal system, catchments with steeper gradients (lower flow path length to gradient ratios) have longer snowmelt water MTTs. As such, these northern Swedish catchments appear to behave similar (with respect to topographic controls on transit times) to the Scottish Highland catchments (Tetzlaff *et al.*, 2009b). Taken together, it can be seen that these landscape and topographic factors are related (Buttle, 2006; Tetzlaff *et al.*, 2009b). That is, wetlands with responsive soils (Bishop *et al.*, 2004; Soulsby *et al.*, 2006b) and/or near-surface impervious ice layers during snowmelt (Laudon *et al.*, 2007) co-evolve with landscape positions with lower gradients. This is conceptually similar to relationships found between aspect and evolution of transit times in several small, mountainous catchments by Broxton *et al.* (2009).

In general, there are significant ($p < 0.02$) relationships between evaluated snowmelt water MTTs and the calculated catchment Pe numbers for the Krycklan catchments (Table III). This is not very surprising as the Pe number (used as a similarity parameter) should be able to discern responses in a given hydrological setting based solely on the catchment structure (Berne *et al.*, 2005; Lyon and Troch, 2007) and should be able to incorporate several of the factors that were significantly related to snowmelt water MTTs into one parameter. One utility of considering such a physics-based similarity parameter

is that it allows for the development of a functional relationship between the hydraulic theory and a catchment's pedo-geomorphological structure. As such, the information contained in such a similarity parameter can be generalized to the traditional hydrologic theory and can be transferred to other locations. Similarity parameters like the catchment Pe number, therefore, have promise with respect to classification schemes for grouping similar small catchments on the basis of the hydrological response. Of course, there are numerous complexities in the Krycklan catchments that complicate and encumber any direct prediction of snowmelt hydrologic response at the small-catchment scale using the catchment Pe number. The catchment Pe number merely provides an empirical relationship between catchment structures to the snowmelt water hydrologic response in the Krycklan research catchments.

This relation between catchment structure and snowmelt water hydrologic response allows some investigation of the influence of climatic changes to ice layers on hydrologic response in these catchments. In this study, we approach this using a simple thought experiment (Section on A Possible Influence of Climatic Changes: A Thought Experiment). This thought experiment does not take into consideration (directly) the possible role of soil hydraulic properties. For example, there is likely a decrease in hydraulic conductivity with depth in the wetlands. As such, subsurface water may not infiltrate through to a depth of 30 cm before flowing laterally as these soils and landscape positions tend to be rather hydrologically reactive (Soulsby *et al.*, 2006b). It is possible that the actual effect of the lack of a wetland soil ice layer may be less than that predicted via our simple thought experiment. In addition, other competing changes may occur under conditions where ice layers do not form (i.e. changes in winter time precipitation form, changes in amount of snow cover and changes in the timing of the melt). While this thought experiment only allows us to roughly estimate the potential change in hydrologic response due to wetland ice layer thawing, it should be noted that any actual thawing of subsurface ice layers will influence flow pathway distributions in northern boreal catchments. Even a modest-to-small shift in flow pathways may greatly influence biogeochemical cycling and/or hydrologic response in these boreal systems (e.g. Bishop *et al.*, 2004; Klamin-der *et al.*, 2006).

Our goal in presenting this wetland ice layer thawing thought experiment is to provide a framework from which we can begin considering the structure of a catchment as a more dynamic system capable of evolving or changing in the time scale of human observation. This is important with regards to the climatic change and its effect on the hydrologic cycle at northern latitudes. It highlights that the various component MTTs that constitute a catchment's long-term MTT may evolve differently in the future. For example, the estimated influence of wetland soil ice is somewhat counter-intuitive in terms of a snowmelt water MTT shift to what might be expected due to climate change. Typically, climate change is expected

to be accelerating the hydrologic cycle (warmer and wetter) in most northern regions (Peterson *et al.*, 2002; Déry *et al.*, 2005) and, thus, we could expect faster catchment MTTs in general due to shifts in the forcing. However, these shifts in catchment forcing may (to some extent) be countered by possible shifts in catchment structure that lead to a dampened hydrologic response. It is therefore likely that climate change presents competing influences on catchment component MTTs that need to be considered. While some component MTTs could tend to decrease due to accelerations in the climatic forcing, some could tend to increase due to changes in the catchment structure or shifts in flow pathways. The balance between these competing influences might have consequences on climatic feedbacks at the catchment scale and warrants further investigation.

CONCLUDING REMARKS

In this study, we estimated snowmelt water MTTs for the 15 Krycklan research catchments located in northern Sweden. Among the different tested catchment indices, snowmelt water MTTs had the highest correlation with the percentage mire wetland area. An empirical model using the catchment Pe number was formulated and used to estimate the potential influence of wetland ice layers on hydrologic response. From this simple thought experiment, there is a potential increase on average of 20 to 45% in snowmelt water MTTs under a scenario when no ice layers form in wetlands. This highlights that the snowmelt water MTTs, and thus also the catchment long-term MTT, may exhibit competing influences on the hydrological and biogeochemical cycles of this and (potentially) other boreal regions.

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