Increasing non-linearity of the storage-discharge relationship during a period of thawing soils and climate warming in Northern Sweden

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May 5, 2020

Abstract

The Arctic is warming at an unprecedented rate. One relatively under researched process is how seasonally frozen soils and changes thereof affect the water cycle. As frozen soils thaw, flow pathways within a watershed open, allowing for enhanced hydrologic connectivity between groundwater and rivers. As the connectivity of flow paths increase, the storage-discharge relationship of a watershed changes. The objective of this study is to quantify trends and spatio-temporal differences in the degree of linearity in the storage-discharge relationships for sixteen watersheds within Northern Sweden throughout the years of 1950 and 2018. We demonstrate a clear increase in non-linearity of the storage-discharge relationship over time for all catchments with twelve out of sixteen watersheds (75%) having a statistically significant increase in non-linearity. Springs have significantly more linear storage-discharge relationships than summer for twelve watersheds (75%), which supports the idea that seasonally frozen soil with a low degree of hydrological connectivity have a linear storage-discharge relationship. For the period considered, spring showed the greater change in storage-discharge relationship trends than summer, signifying changes in recessions are occurring during the thawing period. Separate storage-discharge analyses combined with preceding winter conditions demonstrated that especially cold winters with little snow yield springs and summers with more linear storage-discharge relationships. We show that streamflow recession analysis shows ongoing hydrological change of an arctic landscape as well as offers new metrics for tracking the change across arctic and sub-arctic landscapes.

Introduction

Arctic environments are warming at a faster rate than any other region on earth. This warming is causing concentrated, rapid hydrological changes such as increased freshwater discharge, earlier spring peak flows, increased precipitation and thawing permafrost (Walvoord & Kurylyk, 2016). Climate change influences almost every characteristic of an Arctic watershed snow and rainfall precipitation distributions; vegetation coverage; groundwater storage; permafrost and thawing depth (Hinzman, Bettez, et al., 2005). Permafrost is defined as soil, rock or other natural material that has been frozen for two or more consecutive years (van Everdingen & Association, 1998). We refer to soils that are frozen for less than two years or that thaw every summer, as seasonally frozen soils. Permafrost has been reported to redirect the flow of groundwater (Hinzman, Johnson, Kane, Farris, & Light, 2000). In this context, the role of permafrost connecting and disconnecting groundwater flow and river flow is especially vulnerable to climate change. Apart from permafrost, seasonally frozen soil will likely impact these connections as well. Understanding the effects of seasonally thawing soils on river discharge could provide valuable insights into long-term changes across transitions from permafrost to non-permafrost regions. Moreover as 55-60% of the land surface in the northern hemisphere is currently frozen during winter (Niu & Yang, 2006), with 23.9% of the exposed land area underlain with permafrost (T. Zhang, Barry, Knowles, Heginbottom, & Brown, 2008), understanding how seasonally frozen soils affect the flow of water is crucial to predict hydrological responses to a changed climate.

Based on a synthesis of multiple arctic terrestrial studies examining arctic freshwater processes across different hydrophysiographical regions, Bring et al., (2016) concluded that warming-induced increases in the active layer thickness will likely lead to changes in the storage capacity of groundwater thereby altering river flow dynamics. Walvoord & Kurylyk, (2016) reviewed multiple arctic water flow models and showed that while groundwater exchange and subsurface connectivity is predicted to increase locally, these models are inconclusive on how surface connectivity and river flow dynamics will change at basin scales. Hinzman, Yoshikawa, & Kane, (2005) suggest that evapotranspiration in the Arctic will increase as temperatures increase, leading to dryer soils and lower river flows. Prowse et al., (2015) put forward that the ecological transition, from tundra to boreal, is strongly hydrologically mediated. All of these studies show there is no single dominant permafrost thaw effect on the hydrologic cycle; instead several interacting changes that exacerbate other changes to create complex responses, which differ by region and are typically hard to predict. Predicting such complex and interacting changes in the Arctic is one of the key challenges in hydrology (Peel & Blöschl, 2011; Tetzlaff, Carey, McNamara, Laudon, & Soulsby, 2017). Therefore, observation based approaches are crucial to reveal the ongoing change trajectories, identify dominant processes and build reliable models that can project change trajectories into the future. Although still considered sparse, river discharge is the most commonly available observation throughout the Arctic (Laudon & A. Sponseller, 2017) and contains integrated signals of watershed processes affected by Arctic warming (Bring et al., 2016). In this study, we aim to quantify long-term trends in how watersheds release water (i.e. trends in watershed storage-discharge relationships) throughout Northern Sweden and evaluate if these trends can be attributed to changes in the spatial extent and timing of frozen soils.

Several studies have previously investigated long-term trends in storage-discharge relationships in the Arctic (Bogaart, Van Der Velde, Lyon, & Dekker, 2016; Brutsaert, 2008; Lyon & Destouni, 2010; Lyon et al., 2009; Sjöberg, Frampton, & Lyon, 2013; Watson, Kooi, & Bense, 2013). Typically, these studies assumed linear storage-discharge relationships during winter baseflow conditions and found that groundwater flows more easily (i.e. resistance to flow reduces) into rivers with more pronounced Arctic warming. Lyon et al. (2009) related such changes to an increased active aquifer depth of between 0.7-1.3 cm/y in Northern Sweden. Still, under non-base flow conditions (i.e. following a rainfall or snowmelt event) the relationship between river discharge and water storage is typically nonlinear (Brutsaert & Nieber, 1977; Kirchner, 2009; Wittenberg & Sivapalan, 1999), and cannot easily be related to active flow depths (Bense, Ferguson, & Kooi, 2009). However, under wetter conditions even more pronounced effects of frozen soils on river discharge are expected as seasonal frost hampers infiltration of melt and rainwater into the deeper groundwater, and impacts groundwater outflow into rivers (Ploum et al, 2019; Walvoord & Kurylyk, 2016). Frozen soils are expected to seasonally alter the hydrological connectivity within watersheds by redirecting water dominantly through shallow (above the frozen layer) and deep flow routes (below the frozen layer) towards rivers (Ploum et al., 2019). A change in hydrological connectivity typically alters the functional form of the storage-discharge relationship (i.e. degree of non-linearity) (Lyon & Destouni, 2010).

How does the hydrologic response of Arctic and sub-Arctic watersheds change as the climate warms and the extent of frozen soils recedes? Following up on the study of Ploum et al., (2019), we expect that under thawed conditions deep groundwater, shallow groundwater and overland flow paths all contribute to discharge, while under frozen top soil conditions, shallow flow paths are dominant, although deep groundwater can still contribute. This increase in flow path diversity is expected to occur over both the long-term as permafrost thaws and summer active layer increases with a warming climate, as well as on a seasonal timescale when seasonal frozen soil thaw starts earlier as spring occurs earlier. Previous studies have shown when catchments become wet and the diversity of flow routes increases, increasingly non-linear storage discharge relations are observed (Brutsaert & Nieber, 1977).

Based on these studies, our hypothesis is that as seasonally frozen soils thaw and recede, flow path diversity and thus hydrologic connectivity increases, thereby increasing the non-linearity of the storage-discharge relationship. In this current study, our objective is to test and expand on this hypothesis by quantifying trends and spatio-temporal differences in storage-discharge relationships for sixteen watersheds within Northern Sweden throughout the years of 1950 and 2018. Northern Sweden, has had strong temperatures increases from the start of the 1800's to the 2000's of almost 0.1°C/decade, with a cooling period occurring between 1940's to 1970's (Klingbjer & Moberg, 2003). Multiple proxies for seasonal and intra-annual differences in extent and depth of frozen soils are used to test whether the observed trends and patterns in storage-discharge relationships can be related to thawing soils.

Methods

Concepts: Recession analysis, storage-discharge relationships, and frozen soils.

Recession analysis is a well-established hydrologic method to examine storage-discharge relationships of watersheds and also offers the advantage of being relatively insensitive to meteorological forcing (Tallaksen, 1995). Recession analysis relates the rate of decline of river discharge to the absolute river discharge (recession curve). Under the assumption of a unique relationship between storage, discharge and a closed water balance, recession curves quantify the storage-discharge relationship (Brutsaert, 2008; Kirchner, 2009). Therefore recession curves can be used to better understand the watershed storage-discharge relationship's response to climate change, connecting changes in subsurface groundwater flow with changes in surface flows (Ploum et al., 2019; Shaw & Riha, 2012; Wrona et al., 2016).

Recession curves are typically quantified by fitting a nonlinear storage-discharge relationship to hydrograph recessions during periods when changes in discharge reflect changes in catchment water storage (Brutsaert & Nieber, 1977; Kirchner, 2009; Ploum et al., 2019).

$\frac{\mathrm{dQ}}{\mathrm{dt}} = -Q\frac{\mathrm{dQ}}{\mathrm{dS}} \approx -\alpha Q^{\beta}(1)$

Here, we extend eq. 1 to alleviate the constrains of no-rain and no-evapotranspiration conditions, which allows us to include and account for periods with small amounts of precipitation and evapotranspiration relative to discharge.

$\log\left(-\frac{\mathrm{dQ}}{\mathrm{dt}}\right) - \log\left(1 + \frac{E}{Q} - \frac{P}{Q}\right) = \log(\alpha) + \beta\ log(Q)(2)$

Q is discharge of the river [mm/d], dQ/dt is the rate of discharge decline during the recession [mm/d/d], P is precipitation [mm/d] and E is evapotranspiration [mm/d].dQ/dS is the sensitivity of discharge [d^{-1}] (Kirchner, 2009). In recession analysis, the hydrograph recession is typically plotted in a recession plot withlog $\left(-\frac{\mathrm{dQ}}{\mathrm{dt}}\right)$−log $\left(1 + \frac{E}{Q} - \frac{P}{Q}\right)$ against $\log(Q)$ (Equation 2). When Eq.2 is fitted to the data in this log-log plot, α represents the intercept[$mm^{1-\beta}d^{\beta-2}$], and β is the slope of the recession curve [-]. This technique has been applied to many regions to further understanding of the groundwater and river discharge relationship (Brauer, Teuling, Torfs, & Uijlenhoet, 2013; Dralle, Karst, Charalampous, Veenstra, & Thompson, 2017; Lyon et al., 2015).

Watershed scale recession slopes of rivers can be conceptually interpreted as a measure of hydrologic connectivity as illustrated by a series of buckets (Figure 1). A watershed with one dominant flow path where discharge increases linearly with storage behaves similar to a bucket with a single spigot representing a linear reservoir (β [?] 1) (Figure 1). Observed examples are watersheds with a deeply incised river during baseflow conditions, a confined aquifer below permafrost, or shallow water flow above a frozen soil (Brutsaert & Hiyama, 2012; Lyon & Destouni, 2010; Ploum et al., 2019). In a drained unconfined aquifer both the pressure as well as the saturated thickness control flow (Troch et al., 2013). Such a system can be represented by a bucket with multiple evenly distributed equally sized spigots (flow paths): flow not only depends on the pressure exerted by storage on the spigots but also by the number of spigots. Such a bucket behaves as a nonlinear reservoir with $\beta = 1.5$. A bucket with increasing number of spigots or increasing size of spigots towards the surface will have$\beta > 1.5$. Examples are found in (Kirchner, 2009), (Karlsen et al., 2019) and (Brauer et al., 2013). A special case is when the resistance of the spigots decreases exponentially towards the surface yielding an exponential reservoir ($\beta = 2$). This is frequently observed in relatively flat catchments (e.g. Bogaart et al., 2016; Brauer et al., 2013). Reservoirs where the resistance declines hyperbolically towards the surface yield $\beta > 2$. Several examples are found in literature (Brutsaert & Nieber, 1977; Kirchner, 2009; Troch et al., 2013).

Figure 1

Recession analysis has been used to examine the rate of thawing permafrost, (Brutsaert, 2008; Lyon & Destouni, 2010; Lyon et al., 2009). Brutsaert (2008) focused on baseflow winter (i.e. frozen) conditions when the recession slope (β) can be assumed 1 (linear reservoir). Lyon & Destouni, 2010 used coefficient α (assuming $\beta = 1$) to infer aquifer thickness during late summer, when the active layer extend is maximum in permafrost soils. However, under spring and early summer conditions, we expect that the spatial heterogeneity of actively thickness and hydrological connectivity between aquifers challenges the assumption of linear reservoir behavior ($\beta = 1$). Therefore, we focus on temporal changes in recession slope (β) during spring and summer, which we relate to changes in hydrological connectivity using the interpretation of Figure 1. The spring and summer periods are later separated in order to untangle effects of seasonal soil frost and permafrost on river recessions, with spring period having potential seasonal soil frost and summer as the period with the greatest active layer and without/less seasonal soil frost.

Study Sites and data

Our study sites are situated in Northern Sweden. The sixteen watersheds were chosen because of expected presence of regions with permafrost in the past and present (Brown et al., 1997; Gisnås et al., 2017; Zhang et al., 1999), widespread occurrence of seasonal frozen soils and no current or past known obstruction of the waterways by human intervention following Sjöberg et al. (2013).

Table 1

For the watersheds considered, Övre Abiskojokk, Kaalasjärvi, Tängvattnet and Niavve are the steepest watersheds (Table 1). Övre Abiskojokk, Kaalasjärvi, Killingi and Gauträsk have higher than average elevations of the watersheds, which makes Övre Abiskojokk and Kaalasjärvi the two most mountainous watersheds in this study, both residing next to each other (Table 1). Karesuando, Mertajärvi, Lannavaara and Junosuando have the lowest average elevations, with Mertajärvi being the lowest. Karesuando, Mertajärvi, Lannavaara and Karats have the slightest slopes of the watersheds, with Mertajärvi again being the flattest. Övre Abiskojokk rests in the pass between the mountains that border Norway and Sweden, which brings warm winds from the Baltic Sea. Mertajärvi and Karesuando are near the Finnish border and are the most northern watersheds. Tärendö and Junosuando stretch into the eastern part of the country, characterized with lower elevations than other watersheds (Figure 2). Tärendö is the largest watershed, stretching close to the Gulf of Bothnia. (Sjöberg et al., 2013), followed by Karesuando and Junosuando. The smallest watersheds are Tängvattnet, Skirknäs, Mertajärvi and Övre Abiskojokk (Table 1).

Data availability statement

The discharge data that supports the findings of this study were obtained from the Swedish Meteorological and Hydrological Institute (SMHI), at Vattenwebb. URL: (https://vattenwebb.smhi.se/station/#), the list of catchment used can be found in the supplement. Meteorological data were taken from (SMHI), from the URL: (https://opendata-download-metobs.smhi.se/explore/?parameter=0#). These data were derived from resources available in the public domain. Daily measurements of precipitation, maximum and minimum temperatures and snow depth were used. Evapotranspiration is complex in arctic conditions and studies have shown its importance and the changing influence as climate conditions change (Hinzman & Kane, 1992; Young-Robertson et al., 2018). Maximum and minimum temperatures were used to roughly estimate daily potential evapotranspiration using a Priestley-Taylor approach (Priestley & Taylor, 1972). For watersheds where discharge data is collected separately from meteorological data, the closest geographic meteorological station was used, the name of sites used for each watersheds is in the supplement.

Figure 2

Study Approach

To determine the degree of non-linearity of the storage-discharge relationship (β), we selected hydrograph observations when Q was larger than 0.5 mm/d in order to focus on the wetter periods when we expect a larger effect of frozen soil layers and exclude low flows with deviating recession patterns. In addition, we selected periods when both precipitation and evapotranspiration were less than half of Q. Data was excluded during the first 3 days after a precipitation event to avoid errors in precipitation and timing thereof to affect the estimation of watershed response.

To identify and quantify the potential effects climate warming may have on river recessions, we propose the following four analyses and explain in detail the approach for each.

Temporal trends in recession slopes over time for each catchment. We expect to find increasingly non-linear storage-discharge relationships (i.e. positive trends in β) in a warming climate.

Trends in recession slope are determined from non-overlapping moving time windows of three years, encompassing the entire three years. A too long time window means less recession slopes points and large uncertainty in trends; too short of a time window yields large variance in the data which obscures trends. Both the Mann Kendall and Theil Sen test were used to determine the trend characteristics. The Mann Kendall test assesses the monotonic trend significance, and Theil Sen test examines the robustness of the linear trends. In addition to the Mann Kendall test, the Theil Sen test was used because it is relatively insensitive to outliers and gives a magnitude of the trend (Figure 3b).

Recessions are grouped into spring and summer periods (Figure 3a). During spring periods, we expect that the hydrologic effects of frozen grounds are more influential than during summer periods. Therefore, we expect spring periods have a lower recession slope (more linear storage-discharge relationship) than summer periods.

The start of spring is marked by snowmelt. During this time the ground will often still be frozen. The thawing soils may either be dry and absorb part of the snowmelt or be fully saturated, which will induce overland flow (Kane & Stein, 1983). Start of spring was defined based on a degree day methodology approach proposed by Ploum et al. (2019). Mean daily temperatures are summed but cumulative sums below zero were set to zero. The first day the cumulative sum exceeded 15-degree days was defined as the onset of spring.

Snow depth was irregularly documented in the catchments by SMHI, but when it was not available or very sparse, the depth was roughly approximated by using the recorded data in combination with summing the winter precipitation during freezing conditions (0@C and below).

$\frac{\text{dSWE}}{\text{dt}} = precipitation$ for Temperature [?] 0@C (3)

$\frac{\text{dSWE}}{\text{dt}} = -1.8 * temperature - 0.8 * precipitation$ for Temperature > 0@C (4)

The snowmelt rate is 1.8 [mm SWE/day/C] above 0@C with an added rate of 0.8 times precipitation if any precipitation was recorded (Kustas, Rango, & Uijlenhoet, 1994). When the snow was melted, a 31-day lag was added to allow snowmelt water to leave the watershed. The end of summer was determined by three consecutive days with equal or below 0@C average temperatures. We did not define perfect spring and summer periods but rather divided the runoff season into two contrasting periods each with enough recession events to allow for statistical comparison. Our results are not sensitive to small changes in the end of spring/begin of summer definitions. The lag time could vary between 21 and 31 days and the results did not change significantly. Therefore, we choose a larger lag time to increase spring periods and increase the number of recessions during spring. An accurate onset of spring excluding low winter flows before the spring melt was important.

Spring and summer recessions were compared to determine if the recession slopes were significantly different between periods (Figure 3a and 3d). For this comparison we used the two-sample z-test (Cohen, Cohen, West, & Aiken, 2002).

We analyzed temporal trends for spring and summer recession slopes to identify which season contributed most to the observed yearly trends from analysis 1.

This analysis followed the same method as for the trend over time analysis described in step 1 (above) but was applied separately for spring and summer periods. For each 3-year window, spring and summer recession slopes were determined, if the recessions were significantly different, then it became essential to understand if this difference changed over time as the hydrology in the catchment evolves or if the seasonal recessions have always been constantly different (Figure 3b).

We examined winter temperature influence on recession slopes. We expect recessions following winters with deeply frozen soil behave more linearly than after warm winters. For this analysis into the potential effect of frozen soils, we look at average winter temperature, winter snow depth and a combination of both.

The depth of seasonal freezing depends on winter air temperatures and the thickness of the insulating snow cover (Tingjun Zhang, 2005). The soil potentially freezes deeper during cold winter. Therefore, it potentially takes longer for frozen soil to thaw during spring as compared to warmer winters (Lawrence & Slater, 2010). Hence, recession during springs following cold winters are expected to behave more linearly compared to the warm winters. We split winters into two equally sized groups, half are cold winters and half are warm winters, based on the average winter temperatures (Figure 3a).

Snow depth is another important control on frozen soil depth (Hardy et al., 2001). The snow depth was determined as described in step 2 (Equation 3 and 4) as a proxy for snow cover insulation to approximate frozen soil depth. This method was not intended to quantify depth of snow, but rather qualitatively distinguish between deep and shallow snow depth. The assumption is that snow insulates the ground from freezing temperatures. If seasonally frozen soil depth influences the flow paths and impacts the watershed's recession, then a significant change of recession slope between the snow depth groups would be expected. The final winter indicator of frozen soil depth and extent was a combination of shallow snow depth and winter temperature. The insulation effect of snow peaks at about 40 cm (Tingjun Zhang, 2005), therefore to obtain the shallow snow depth effect, we took a little more than half of 40 cm (25 cm - SWE of 2.5 cm). Using the previously calculated snow depth, we took only the periods with SWE less than 2.5 cm. The temperatures during these annual periods were summed, and then the years were divided into two groups to create shallow snow cold winters and shallow snow warm winters (Figure 3a). For all three indicators of frozen soil conditions, we used the two-sample z-test to determine significant differences between the selected periods (Figure 3a).

Figure 3

Figure 3d shows a z-test graph with confidence lines and a shaded purple area, which correlates to the purple arrow in Figure 3e. The arrow is a representation of the area between the recession lines: the larger the arrow, the greater the difference. The direction of the arrows indicates findings, upwards implies a result anticipated by our hypothesis and downwards implies a result divergent from our hypothesis.

Results

Trend over time

Our analyses demonstrated a widespread increase in non-linearity of recessions in Northern Sweden for all seasons combined (Figure 4). Ten of sixteen watersheds show a significant trend of increasing non-linearity in the storage-discharge relationship (i.e. increasing β) for both trend tests (Mann Kendall and Theil Sen) and no watershed had a significant negative trend. Overall, fourteen of the sixteen watersheds had a positive trend, and twelve watersheds had a significant positive trend over time for the Theil Sen test (Table 2). On average, recession slopes increased 0.006 Y^{-1} with mostly linear recessions (β = 0.8-1.3) in the period 1950-1970 increasing toβ = 1.3-2.2 during 2010-2018. Following our hypothesis, a trend of increasing non-linearity in recession slopes suggests increased diversity of flow routes contributing to stream discharge.

Table 2

It was not until the 1980's and 1990's when recession slopes started to increase (Figure 4). Mertajärvi, Tärendö, Niavve, Karats, Stenudden, Laisvall, Gauträsk, Tängvattnet and Solberg had statistically significant recession slope increases for both statistical tests. Övre Abiskojokk, Junosuando, and Skirknäs were significant for only the Theil Sen test.

Figure 4

Stenudden, Niavve and Karats are geographically close and had similar recession slopes and trends. Of these, Karats showed the strongest increase in non-linearity during the last decade (Figure 4). Solberg, Skirknäs, Gauträsk and Tängvattnet are also geographically close (Figure 2). Tängvattnet was the lowest of the four with more linear recession slopes, it had an increase in trend over time, but Tängvattnet starts with a recession slope under 1.0 and it did not increase above 1.0 until 1995. Junosuando's recession slope was the only significant negative trend slope of the watersheds, having significance only for the Theil Sen test. Junosuando's gauging site was originally situated upstream of a river bifurcation, and now the bifurcation is currently upstream of the site, we suspect this to be the cause of the negative slope.

Spring and summer analysis

Our hypothesis that spring recessions are more linear than summer recessions was substantiated. Twelve out of sixteen watersheds had more linear spring recession slopes and more non-linear summer recession slopes (Table 2). The watersheds with significant results were designated with thick purple arrows (Figure 5). Mertajärvi, Junosuando, Stenudden and Tängvattnet were the watersheds without a significant difference between summer and spring periods. Junosuando has the bifurcation, which might explain the insignificance.

The Mann Kendall test yielded six watersheds with a significant summer trend, Mertajärvi, Kaalasjärvi, Stenudden, Killingi, Niavve and Tängvattnet (Table 2). Thirteen summer recession trends are significant for the Theil Sen estimator with only Junosuando having a negative slope for summer trends. The Mann Kendall test yielded only one watershed with a significant spring trend, Tärendö. The Theil Sen estimator determined nine spring recession trends were significant. For the significant spring trends, seven watersheds had a positive slope (Figure 5a).

Figure 5

When comparing the two seasonal periods, summer had the greater number of significant recession slopes, but increases in recession slopes (i.e. trends) were generally larger during spring (Figure 5a). In Tärendö, Gauträsk, Tängvattnet, Solberg, (Figure 5a) yearly trends in recessions slopes seem dominated by spring changes, only Mertajärvi and Niavve have dominant summer changes. For all other watersheds, a significant trend in recession slope could not clearly attributed to either spring or summer but was driven by both periods.

Attribution to winter conditions

Table 3

Twelve of sixteen watersheds had recession slopes closer to linearity for colder winters than for warmer winters as shown in Table 3. Ten of the twelve watersheds had a significant difference. None show significant higher non-linearity in cold winter compared to warm winter.

The first step to analyze deep and shallow snow depth was to separate deeply frozen soils from shallow frozen soils. Without available continuous frozen soil data for the watersheds, determining when frozen soil depth was at its greatest depth was done by assuming shallow snow depth does not insulate as much as deep snow depth. Our results were inconclusive. There was geographical clustering to the significant watersheds (Table 3, Figure 5b), Övre Abiskojokk, Kaalasjärvi, Killingi and Tärendö had a higher recession slope when there was deep snow packs. The four are part of the same mountain range. From our results, we cannot conclude how a watershed's recession slope will react to a change in snow depth.

While looking at Figure 3a, for deep and shallow snow depth, shallow snow depth for Niavve happens more in recent years, leading us to believe that there has been a change in snow depths over time. As soil frost is controlled by both winter temperature and snow insulation, our final soil frost indicator is winter temperature while snow depth is shallow. As shallow snow signified poor insulation, cold winters during shallow snow would result in a deeper frozen layer than warm winters during shallow snow. This had consistent results. Six watersheds had significant differences between the cold and warm winters during shallow snow periods. While it is fewer watersheds than expected, the significant watersheds had increased non-linearity in recession slopes during warm winters than cold winters, echoing our anticipated results for warm and cold winters.

Because many of the warmer winters are within recent years, we wanted to check if the significant difference in recession slopes between warm and cold winters was due to winter temperature differences between individual years or rather related to a general increase in temperatures during the recent warm decades. Additionally, we wanted to establish if winter temperature characteristics impacted the recession slopes during the periods before clear changes in overall recession slope were visible (the period up to 1990) similarly as during the entire period. We selected two watersheds with the longest datasets, Karats and Niavve, split the datasets between when their recession slopes were constant and when their recession slopes started to increase and performed z-test for all of the winter characteristics we had examined previously. For this period (1951-1990) we found there to be no significant difference between warm and cold winters or shallow snow depth and deep snow depth for either catchment. During 1951-1990, for shallow snow in cold and warm winters, Karats is significantly different. However, for the entirety of Karats' dataset (1951-2018), it was not significant (Table 3). We should note there is less data if we limit the analyses to pre-1990, which increases uncertainty and decreases the probability of finding significant differences.

Discussion

Recession slope trends over time

Watersheds with data starting in the 1950's had yearly average recession slopes around 1.0, which have significantly increased to values around 1.5 through the present. We find recession slopes as low as 0.7 and as high as 2.6 enveloping the entire range of slopes found by theoretical consideration (Troch et al., 2013). (Brauer et al., 2013; Karlsen et al., 2019; Kirchner, 2009; Ploum et al., 2019; Sjöberg et al., 2013; Troch et al., 2013; Van Der Velde, Lyon, & Destouni, 2013) indicated that watersheds analyzed with different regression methods will result in different recession slope values. Therefore, comparison of recession slopes between studies using different methods has to be done with care. In general, the direction of differences between watersheds and between periods of the same watershed using the same method are expected to be comparable (Shaw & Riha, 2012). Within our datasets, there has been no known physiographic changes, such as topography, artificial lakes, or changes in discharge measuring method; thus, the changes in recession slopes come from other aspects, such as land cover change, or thawing permafrost. If soil frost thaw is truly causing a change in recession slope, it is mainly by the increasing depth of active layer as the soil thaws, which contributes to a larger diversity in flow paths contributing to stream discharge. The recession slope has been shown to change with changes in land cover and soil type (Bogaart et al., 2016). In addition to significant differences in seasonal recessions found by (Karlsen et al., 2019; Ploum et al., 2019), our research contributes with showing significant increasing non-linearity of recession behavior since 1950.

Ten recession slope trends over time are positive and significant for both statistical tests, while no recession slope trends are negative and are significant for both statistical tests. Sjöberg et al. (2013) found for the same catchments that late summer recession intercept had increasing trends, along with increasing minimum winter discharge trends. While these two characteristics are affected by thawing permafrost, the extent and agreement between late summer recession intercept and minimum winter discharge trends varied thought the watersheds. Lyon & Destouni (2010) and Sjöberg et al. (2013) focused on late summer for recession analysis and winter for minimum discharge analyses, during winter when river discharge originates from sub-frost groundwater, a recession slope of 1 can be assumed. They found increasing intercepts of the recession is related to changes in the active layer. We show that for spring and summer conditions during recent decades linear reservoir behavior ($\beta = 1$) cannot be assumed. Moreover, we confirmed the effects of a warming arctic on river discharge would be more pronounced during spring conditions, than during summer conditions by showing the omnipresent trend of increasing non-linearity in storage-discharge relationships (increasing slopes in the recession plots) and that these observed changes are dominantly caused by changes in spring.

Groundwater flow though thawing soils is a complex process. Arctic watersheds have been documented to be changing over a long period of time, with streamflow and precipitation increasing, land cover shifts, changes in soils, decline in permafrost and seasonally frozen soil depth and changes in the snow cover extent and timing (Bring et al., 2016; Hirota et al., 2006; Prowse et al., 2015; Wrona et al., 2016). We provide overwhelming evidence that discharge recession slopes are increasing in Northern Sweden. This means that storage-discharge relationships are becoming increasingly non-linear; under low to intermediate wetness conditions, water is stored more effectively within the watersheds, while under wet conditions water is released faster, making river flows more unpredictable and uncertain. It is clear from these results that hydrological models which aim to predict changes in artic river discharges caused by climate change cannot rely on constant storage-discharge relationships, but need to account for climate warming effects on the physical watershed properties that underlie storage-discharge relationships.

Seasonal recession slopes

Ploum et al., (2019) explored storage-discharge relationships for Övre Abiskojokk, a watershed included in our study, and concluded recessions slopes were likely influenced by soil frost. Ploum et al (2019) hypothesized that summer recessions slopes would be larger than spring recession slopes due to the winter soil frost being thawed further in summer than in spring. Additionally, Ploum et al (2019) showed that the observed direction of the difference between spring and summer could not be explained by summer evapotranspiration. Similarly, Karlsen et al. (2019) consistently found higher summer recessions slopes than in spring in the boreal catchment Krycklan. With 15 more watersheds, we also find storage-discharge relationships with consistently higher slopes, (higher non-linearity), in summer than in spring (Table 2). We interpret this robust finding in terms of flow paths and storage. The subsurface volume available for water storage within a watershed increases from spring to summer. When conditions are wet and storages full, a more immediate and strong response of discharge to additional rainfall can be expected in summer compared to spring, although due to snowmelt, discharges in spring tend to be higher. In line with findings of Karlsen et al. (2019), it is apparent that spring and summer recession are two separate recessions and therefore the difference between the seasons is to be expected.

Spring and summer recession slope trends

We find spring recession slopes have had greater changes compared to summer. However, our results for spring and summer trends are not completely straightforward. Although trend analysis with year-round data shows clear increases in non-linearity of the storage-discharge relationship, separate trend analyses for spring and summer recessions do not clearly yield one dominant period that controls the observed yearly trend in recessions. For twelve watersheds, summer has the greater recession slope (i.e. more non-linear) (Table 2). Spring has lower recession slopes when compared to summer, but over time, we see spring as the season undergoing the greatest change. Frampton, et al., (2011) suggested that thawing soils lead to increasing flow pathway diversity, which in turn will decrease seasonal variability in water flow. This can explain why the summer recessions observed in this study do not have strong trends as this is the period when thawing soils are at their greatest depths. However, when permafrost is omnipresent within the watershed and permafrost is disappearing this will also strongly affect summer discharge recessions. Potentially, a stronger effect could be expected in summer rather than during spring when soils are still primarily frozen from the previous winter.

Attribution to winter conditions

Ploum et al. (2019) suggested winter air temperatures have an influence over recession slopes. Following this logic, if winter air temperatures have an effect on recession slopes, we would see impact on recession analysis when our dataset is separated by years following cold and warm winters. For the region considered, there has been increasing winter temperatures since the start of 1900 (Luterbacher, Dietrich, Xoplaki, Grosjean, & Wanner, 2004). With no exceptions, all ten significantly different watersheds have a higher recession slope following warm winters than cold winters. Therefore, it can be concluded that there is a significant increase in non-linear recession slopes during warmer winters than colder winters for these sub-arctic watersheds (Figure 5b). Our hypothesis was that this pattern is because warmer winters have a shallower frozen soil layer, which thaws quicker than after winters with a deeper frozen soil layer. However, we could not confirm this pattern when examining data before 1990 for the two watershed with the longest records. St. Jacques & Sauchyn (2009) also found that winter air temperatures affecting streamflow can be seen; they suggested that these changes are caused by the thawing soil that increases infiltration and flow paths.

Payn et al. (2012) stated that correlation between flow paths and surface attributes decreased during recession leading to subsurface structures gaining influence on the flow paths. Subsurface structures can be many things, including permafrost, geology of the watershed and seasonally frozen soil. Snow is an important feature for frost depth as it insulates the ground from heat loss. Hirota et al. (2006) found correlation between increasing snow depth and decreasing seasonally frozen soil depth. Seasonally frozen soil is a complex process that cannot be simplified with just a snow depth assumption. Eleven of the watersheds do show significant different recession slopes between deep and shallow winter snow packs, but there is no clear pattern. Out of eleven significant watersheds, six watersheds show the expected higher recession slope during deep snow depths. It is also meaningful to recognize that recent years are having smaller snow depths during winter in this region (Figure 3a). We can maintain that there is a difference in recession slopes between shallow and deep snow depth, but with deeper snow depth becoming less common while winters temperatures are increasing, the link between deep snow depth and soil frost might be diminishing.

Shallow snow depth (below 25cm) periods and winter air temperatures were combined to identify years with more and less than average frozen soil depth. We expected soils to freeze deeper when cold temperature occur during periods with little snow (Hardy et al., 2001; Osterkamp, 2007). Six watersheds had significant differences, with higher recession slopes for shallow snow warm winters (Table 2) showing shallow frozen ground does have an effect on recession slopes. When shallow snow depth was separated by winter temperatures, watersheds had significantly lower recessions slope during cold temperatures compared to warm temperatures, indicating the lesser extent of soil frost during warm winters. Using snow depth and winter air temperatures in combination to determine the extremes of frozen soil depth yielded more unambiguous results than just snow depth showing that six out of sixteen catchments have significantly more non-linear recession slopes during shallow snow warm winters. The majority of watersheds did not have significance, but none of the catchments were significantly more non-linear recession slopes during shallow snow cold winters. Kohler et al., (2006) modeled the snow depth in Abisko and concluded increasing snow depth averages over the last century. Naivve's snow depth trend and Abisko's snow depth trend indicate different watersheds have different snow depth responses to climate change. The increasing or decreasing of snow depth has been seen in multiple catchments in Sweden, Åkerman & Johansson (2008) found five of their nine watersheds to having increasing snow depths. Because our catchments are undergoing unique snow depth changes over time, the climatic shift towards an increase or decrease in snow depth in various watersheds could explain why some watersheds have significance during shallow snow depths between cold and warm winters and others do not. Warm winters cause increased non-linear recession slopes, and shallow snow depths lead to greater frozen soils depths, these two winter conditions are becoming regular in the arctic and counterbalance each other's effect on the recession slope.

We provide evidence that recession slopes depend on preceding winter conditions, which controls when flow paths start to flow and how many are available. As recent winters globally have been some of the hottest on record (LeComte, 2020), we wanted to determine if similar significant results can be found in the first half of our datasets, when recession slopes were not increasing so quickly. For warm and cold winters, there was no significance difference, nor was there significance between shallow and deep snow depths. Karats before 1990, did show a significant difference between cold and warm winters during shallow snow periods, implying the sudden increase in recession slope from 1990 onwards potentially masked the influence of snow depth on recession slopes. Discovering the point when frozen soil thaws can lead to recognizing changes in the watershed recession through a transitional point of permafrost thaw rather than the results of the arctic adapting to climatic changes during the last decades.

Effects of frozen soil and permafrost on river recessions: A conceptual model.

Based on our results and results of previous studies we summarized our finding into a conceptual model (Figure 6). We found approximately linear storage-discharge relationships during spring for all catchments. Moving into summer, these storage-discharge relationships become more non-linear, a similar transition we find with the storage-discharge relationship trend over time. When permafrost thaws or the extent and depth of seasonally frozen soils reduces both the spring and summer storage-discharge relationship become more non-linear. We even tend to see that spring recessions change more than summer recessions. Although conceptually straightforward, it remains a challenge to confirm this conceptual model with a physically based model. First steps have been made in this direction by (Frampton et al., 2011; Sjöberg et al., 2016; Walvoord, Voss, & Wellman, 2012). These studies looked at a numerical model for non-isothermal, three-phase flow of air and water or recession intercepts and annual minimum discharge determined by the interactions between groundwater and permafrost or a numerical simulation of flow paths and water budget with winter base flows. Such a dynamic modelling effort is out of the scope of this research but is crucial in making progress in the prediction of changing water flows and dynamics of river discharges within the warming arctic.

Figure 6

Seasonally frozen soils along with decreasing amounts of permafrost have an effect on groundwater flow in arctic catchments (Figure 6). Recession slopes in this study's catchments are becoming increasingly non-linear, though the degree of change depends on the watershed's topography, differences in bedrock and surficial geology and current continuity of permafrost presence. We hypothesized that recession slopes are partly controlled by frozen ground and in turn, react to thawing ground. Our results support this hypothesis, but we cannot exclude that other changes within the watersheds could have similar effects on recessions. This study did not examine the potential effect of soil moisture on the recession slope. Other studies are suggesting arctic catchments are becoming wetter, which may also change the storage/discharge relationship, and consecutively, the recession slope (Raynolds & Walker, 2016; Rowland et al., 2010). The recession slope change could also be caused by land cover change, as vegetation migrates further north to the Arctic, different flora would have different water needs influencing the hydrological response, along with different evapotranspiration rates, and therefore there would be a change in water yield flowing to the rivers (Costa et al., 2003).

While we wanted to answer how permafrost and seasonally frozen soil thaw affect recession slopes, the extent of permafrost in Sweden is mostly discontinuous or sporadic. Although continuous permafrost has been present in Sweden, the extent and timing appears uncertain as permafrost detection methods have been limited in the past. (Gisnås et al., 2017; Kullman, 1989; Lagerbäck & Rodhe, 1985; Sjöberg et al., 2013). The remaining permafrost in Sweden is in mountainous regions. Gruber & Haeberli (2009) states for mountainous regions, permafrost is impacted by the slope of a watershed along with topography, elevation and strong winds dictating snow cover conditions. If the lingering permafrost is in alpine regions, next steps should include permafrost in flat regions to see if we find similar changing patterns.

Conclusion

We show watersheds in Northern Sweden have been undergoing a significant change in the recession behavior since 1950 and especially since 1990. The storage-discharge relationships of thirteen out of sixteen investigated watersheds has become more non-linear, with in-general a larger change in spring than summer. This means these watersheds are better able to store their water under low to medium wetness conditions but release their water more instantaneously under wet conditions, making river discharge in the Arctic more unpredictable. We hypothesized that these changes are primarily caused by disappearing permafrost and a reduced depth of seasonal soil frost. Although several of our data-analysis tests confirm parts of this hypothesis, without solid knowledge of the extent of permafrost, depth of winter frozen soils and summer active layer depth, this link remains speculative. Moreover, it is likely other landscape changes such as vegetation change, soil organic matter and soil biota changes also strongly affect water flow paths thusly contributing to the observed changes in storage-discharge relationships (Figure 6). Our results clearly demonstrate that predicting arctic river discharges in a warming climate cannot rely on models that assume fixed storage-discharge relationships, but requires models that describe how warming affects the physical properties of watersheds that underlie the storage-discharge relationships.

The main contribution of this study is that we established hydrological change trajectories of the storage-discharge relationships for terrestrial Northern Sweden. Because of the complexity of the changing Artic in which climate, vegetation, soils, ice, and landscape form (e.g. river systems) interact, the future of the Artic is very difficult to predict. Understanding and predicting the effect of further Arctic warming starts with establishing such ongoing change trajectories and use process-based models to reproduce and extrapolate into the future.

References

Åkerman, H. J., & Johansson, M. (2008). Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafrost and Periglacial Processes* , *19* (3), 279–292. https://doi.org/doi:10.1002/ppp.626

Bense, V. F., Ferguson, G., & Kooi, H. (2009). Evolution of shallow groundwater flow systems in areas of degrading permafrost. *Geophysical Research Letters* , *36* (22). https://doi.org/doi:10.1029/2009GL039225

Bogaart, P. W., Van Der Velde, Y., Lyon, S. W., & Dekker, S. C. (2016). Streamflow recession patterns can help unravel the role of climate and humans in landscape co-evolution. *Hydrology and Earth System Sciences* , *20* (4), 1413–1432. https://doi.org/10.5194/hess-20-1413-2016

Brauer, C. C., Teuling, A. J., Torfs, P. J. J. F., & Uijlenhoet, R. (2013). Investigating storage-discharge relations in a lowland catchment using hydrograph fitting, recession analysis, and soil moisture data. *Water Resources Research* , *49* (7), 4257–4264. https://doi.org/doi:10.1002/wrcr.20320

Bring, A., Fedorova, I., Dibike, Y. B., Hinzman, L. D., Mård, J., Mernild, S. H., ... Woo, M. (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research G: Biogeosciences* . https://doi.org/10.1002/2015JG003131

Brown, J., Heginbottom, J. A., Melnikov, E. S., Geological, C. P., & Survey, M. A. P. (1997). *Circum-Arctic map of Permafrost and Ground-ice Conditions. US 45 United States Geological Survey Denver Colorado* . US Geological Survey Reston, VA.

Brutsaert, W. (2008). Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. *Water Resources Research* , *44* (2). https://doi.org/10.1029/2007WR006518

Brutsaert, W., & Hiyama, T. (2012). *The determination of permafrost thawing trends from long-term streamflow measurements with an application in eastern Siberia* . *Journal of Geophysical Research (Atmospheres)* (Vol. 117). https://doi.org/10.1029/2012JD018344

Brutsaert, W., & Nieber, J. L. (1977). Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research* , *13* (3), 637–643. https://doi.org/10.1029/WR013i003p00637

Cohen, J., Cohen, P., West, S., & Aiken, L. (2002). *Applied Multiple Regression/Correlation for the Behavioral Sciences* . Psychology Press.

Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* ,*283* (1–4), 206–217. https://doi.org/10.1016/S0022-1694(03)00267-1

Dralle, D. N., Karst, N. J., Charalampous, K., Veenstra, A., & Thompson, S. E. (2017). Event-scale power law recession analysis: quantifying methodological uncertainty. *Hydrology and Earth System Sciences* , *21* (1), 65–81. https://doi.org/10.5194/hess-21-65-2017

Frampton, A., Painter, S. L., Lyon, S. W., & Destouni, G. (2011). Non-isothermal, three-phase simulations of near-surface flows in a model permafrost system under seasonal variability and climate change. *Journal of Hydrology* , *403* (3–4), 352–359. https://doi.org/10.1016/j.jhydrol.2011.04.010

Gisnas, K., Etzelmuller, B., Lussana, C., Hjort, J., Sannel, A. B. K., Isaksen, K., ... Frampton, A. (2017). Permafrost map for Norway, Sweden and Finland. *Permafrost and Periglacial Processes* ,*28* (2), 359–378.

Gruber, S., & Haeberli, W. (2009). Mountain Permafrost. In R. Margesin (Ed.), *Permafrost Soils* (pp. 33–44). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-69371-0_3

Hardy, J. P., Groffman, P. M., Fitzhugh, R. D., Henry, K. S., Welman, A. T., Demers, J. D., ... Nolan, S. (2001). Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. *Biogeochemistry* , *56* (2), 151–174. https://doi.org/10.1023/A:1013036803050

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin III, F. S., Dyurgerov, M. B., Fastie, C. L., ... Yoshikawa, K. (2005). Evidence and implications of recent climate change in Northern Alaska and other Arctic regions. *Climatic Change* , *72* , 251–298. https://doi.org/10.1007/s10584-005-5352-2

Hinzman, L. D., Johnson, R. A., Kane, D. L., Farris, A. M., & Light, G. J. (2000). Measurements and modeling of benzene transport in a discontinuous permafrost region. In *Contaminant Hydrology: Cold Regions Modeling* (pp. 175–237). Lewis Publishers.

Hinzman, L. D., & Kane, D. L. (1992). Potential Response of an Arctic Watershed During a Period of Global Warming. *Journal of Geophysical Research* , *97* (D3), 2811–2820. https://doi.org/10.1029/91JD01752

Hinzman, L. D., Yoshikawa, K., & Kane, D. L. (2005). Permafrost controls on hydrological processes in a changing climate. *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005 World Water and Environmental Resources Congress* . https://doi.org/10.1061/40792(173)255

Hirota, T., Iwata, Y., Hayashi, M., Suzuki, S., Hamasaki, T., Sameshima, R., & Takayabu, I. (2006). Decreasing soil-frost depth and its relation to climate change in Tokachi, Hokkaido, Japan. *Journal of the Meteorological Society of Japan* , *84* (4), 821–833. https://doi.org/10.2151/jmsj.84.821

Kane, D. L., & Stein, J. (1983). Water movement into seasonally frozen soils. *Water Resources Research* , *19* (6), 1547–1557. https://doi.org/10.1029/WR019i006p01547

Karlsen, R. H., Bishop, K., Grabs, T., Ottosson-Lofvenius, M., Laudon, H., & Seibert, J. (2019). The role of landscape properties, storage and evapotranspiration on variability in streamflow recessions in a boreal catchment. *Journal of Hydrology* , *570* , 315–328. https://doi.org/10.1016/j.jhydrol.2018.12.065

Kirchner, J. W. (2009). Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research* , *45* (2). https://doi.org/10.1029/2008WR006912

Klingbjer, P., & Moberg, A. (2003). A composite monthly temperature record from Tornedalen in northern Sweden, 1802–2002.*International Journal of Climatology* , *23* (12), 1465–1494. https://doi.org/10.1002/joc.946

Kohler, J., Brandt, O., Johansson, M., & Callaghan, T. (2006). A long-term Arctic snow depth record from Abisko, northern Sweden, 1913-2004. *Polar Research* . https://doi.org/10.1111/j.1751-8369.2006.tb00026.x

Kullman, L. (1989). Geoecological Aspects of Episodic Permafrost Expansion in North Sweden. *Geografiska Annaler: Series A, Physical Geography* , *71* (3–4), 255–262. https://doi.org/10.1080/04353676.1989.11880293

Kustas, W. P., Rango, A., & Uijlenhoet, R. (1994). A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research* , *30* (5), 1515–1527. https://doi.org/10.1029/94WR00152

Lagerback, R., & Rodhe, L. (1985). Pingos in Northernmost Sweden.*Geografiska Annaler: Series A, Physical Geography* ,*67* (3–4), 239–245. https://doi.org/10.1080/04353676.1985.11880149

Laudon, H., & A. Sponseller, R. (2017). *How landscape organization and scale shape catchment hydrology and biogeochemistry: insights from a long-term catchment study* . *Wiley Interdisciplinary Reviews: Water* . https://doi.org/10.1002/wat2.1265

Lawrence, D. M., & Slater, A. G. (2010). The contribution of snow condition trends to future ground climate. *Climate Dynamics* . https://doi.org/10.1007/s00382-009-0537-4

LeComte, D. (2020). A Decade of Extremes: The Top-10 Record-Breaking Events of Recent Years. *Weatherwise* , *73* (2), 14–23. https://doi.org/10.1080/00431672.2020.1705698

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., & Wanner, H. (2004). European Seasonal and Annual Temperature Variability, Trends, and Extremes Since 1500. *Science* , *303* (5663), 1499 LP – 1503. https://doi.org/10.1126/science.1093877

Lyon, S. W., & Destouni, G. (2010). Changes in Catchment-Scale Recession Flow Properties in Response to Permafrost Thawing in the Yukon River Basin. *International Journal of Climatology* , *30* (14), 2138–2145. https://doi.org/10.1002/joc.1993

Lyon, S. W., Destouni, G., Giesler, R., Humborg, C., Morth, M., Seibert, J., ... Troch, P. A. (2009). Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis. *Hydrology and Earth System Sciences* , *13* (5), 595–604. https://doi.org/10.5194/hess-13-595-2009

Lyon, S. W., Koutsouris, A., Scheibler, F., Jarsjo, J., Mbanguka, R., Tumbo, M., ... van der Velde, Y. (2015). Interpreting characteristic drainage timescale variability across Kilombero Valley, Tanzania. *Hydrological Processes* , *29* (8), 1912–1924. https://doi.org/doi:10.1002/hyp.10304

Niu, G.-Y., & Yang, Z.-L. (2006). Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale. *Journal of Hydrometeorology* , *7* (5), 937–952. https://doi.org/10.1175/JHM538.1

Osterkamp, T. E. (2007). Characteristics of the recent warming permafrost in Alaska. *Journal of Geophysical Research: Earth Surface* , *112* (2), F02S02. https://doi.org/10.1029/2006JF000578

Payn, R. A., Gooseff, M. N., McGlynn, B. L., Bencala, K. E., & Wondzell, S. M. (2012). Exploring changes in the spatial distribution of stream baseflow generation during a seasonal recession. *Water Resources Research* , *48* (4). https://doi.org/10.1029/2011WR011552

Peel, M. C., & Bloschl, G. (2011). Hydrological modelling in a changing world. *Progress in Physical Geography* , *35* (2), 249–261. https://doi.org/10.1177/0309133311402550

Ploum, S. W., Lyon, S. W., Teuling, A. J., Laudon, H., & van der Velde, Y. (2019). Soil frost effects on streamflow recessions in a subarctic catchment. *Hydrological Processes* , *33* (9), 1304–1316. https://doi.org/10.1002/hyp.13401

Priestley, C. H. B., & Taylor, R. J. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters.*Monthly Weather Review* , *100* (2), 81–92. https://doi.org/10.1175/1520-0493(1972)100<0081:otaosh>2.3.co;2

Prowse, T. D., Bring, A., Mard, J., Carmack, E., Holland, M. M., Instanes, A., ... Wrona, F. J. (2015). Arctic Freshwater Synthesis: Summary of key emerging issues. *Journal of Geophysical Research: Biogeosciences* , *120* (10), 1887–1893. https://doi.org/10.1002/2015JG003128

Raynolds, M. K., & Walker, D. A. (2016). Increased wetness confounds Landsat-derived NDVI trends in the central Alaska North Slope region, 1985-2011. *Environmental Research Letters* , *11* (8). https://doi.org/10.1088/1748-9326/11/8/085004

Rowland, J. C., Jones, C. E., Altmann, G., Bryan, R., Crosby, B. T., Geernaert, G. L., ... Wilson, C. J. (2010). Arctic landscapes in transition: Responses to thawing permafrost. *Eos* , *91* (26), 229–230. https://doi.org/10.1029/2010EO260001

Shaw, S. B., & Riha, S. J. (2012). Examining individual recession events instead of a data cloud: Using a modified interpretation of dQ/dt-Q streamflow recession in glaciated watersheds to better inform models of low flow. *Journal of Hydrology* , *434 –435* , 46–54. https://doi.org/10.1016/j.jhydrol.2012.02.034

Sjoberg, Y., Coon, E. T., K. Sannel, A. B., Pannetier, R., Harp, D., Frampton, A., ... Lyon, S. W. (2016). Thermal effects of groundwater flow through subarctic fens: A case study based on field observations and numerical modeling. *Water Resources Research* ,*52* (3), 1591–1606. https://doi.org/doi:10.1002/2015WR017571

Sjoberg, Y., Frampton, A., & Lyon, S. W. (2013). Using streamflow characteristics to explore permafrost thawing in northern Swedish catchments. *Hydrogeology Journal* , *21* (1), 121–131. https://doi.org/10.1007/s10040-012-0932-5

St. Jacques, J.-M., & Sauchyn, D. J. (2009). Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters* ,*36* (1). https://doi.org/10.1029/2008GL035822

Tallaksen, L. M. (1995). A review of baseflow recession analysis.*Journal of Hydrology* , *165* (1–4), 349–370. https://doi.org/10.1016/0022-1694(94)02540-R

Tetzlaff, D., Carey, S. K., McNamara, J. P., Laudon, H., & Soulsby, C. (2017). The essential value of long-term experimental data for hydrology and water management. *Water Resources Research* . https://doi.org/10.1002/2017WR020838

Troch, P. A., Berne, A., Bogaart, P. W., Harman, C., Hilberts, A. G. J., Lyon, S. W., ... Verhoest, N. E. C. (2013). The importance of hydraulic groundwater theory in catchment hydrology: The legacy of Wilfried Brutsaert and Jean-Yves Parlange. *Water Resources Research* , *49* (9), 5099–5116. https://doi.org/doi:10.1002/wrcr.20407

Van Der Velde, Y., Lyon, S. W., & Destouni, G. (2013). Data-driven regionalization of river discharges and emergent land cover-evapotranspiration relationships across Sweden. *Journal of Geophysical Research Atmospheres* , *118* (6), 2576–2587. https://doi.org/10.1002/jgrd.50224

van Everdingen, R. O., & Association, I. P. (1998).*Multi-language glossary of permafrost and related ground-ice terms in chinese, english, french, german...* Arctic Inst. of North America University of Calgary.

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal* , *15* (6), 0. https://doi.org/10.2136/vzj2016.01.0010

Walvoord, M. A., Voss, C. I., & Wellman, T. P. (2012). Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. *Water Resources Research* , *48* (7). https://doi.org/10.1029/2011WR011595

Watson, V., Kooi, H., & Bense, V. F. (2013). Potential controls on cold-season river flow behavior in subarctic river basins of Siberia. *Journal of Hydrology* , *489* , 214–226. https://doi.org/10.1016/j.jhydrol.2013.03.011

Wittenberg, H., & Sivapalan, M. (1999). Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. *Journal of Hydrology* , *219* (1–2), 20–33. https://doi.org/10.1016/S0022-1694(99)00040-2

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mard, J., Myers-Smith, I. H., ... Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences* , *121* (3), 650–674. https://doi.org/10.1002/2015JG003133

Young-Robertson, J. M., Raz-Yaseef, N., Cohen, L. R., Newman, B., Rahn, T., Sloan, V., ... Wullschleger, S. D. (2018). Evaporation dominates evapotranspiration on Alaska's Arctic Coastal Plain. *Arctic, Antarctic, and Alpine Research* , *50* (1), e1435931. https://doi.org/10.1080/15230430.2018.1435931

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., & Brown, J. (2008). Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography* ,*31* (1–2), 47–68. https://doi.org/10.1080/10889370802175895

Zhang, Tingjun. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics* ,*43* (4). https://doi.org/10.1029/2004RG000157

Zhang, Tingjun, Barry, R. G., Knowles, K., Heginbottom, J. A., & Brown, J. (1999). Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography* ,*23* (2), 132–154. https://doi.org/10.1080/10889379909377670

Supplement

Table 4

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