Received: 11 March 2020 | Accepted: 30 June 2020
DOI: 10.1002/hyp.13860

RESEARCH ARTICLE

WILEY

Increasing non-linearity of the storage-discharge relationship in sub-Arctic catchments

Alexa M. Hinzman[1] | Ylva Sjöberg[4] | Steve W. Lyon[2] | Stefan W. Ploum[3] | Ype van der Velde[5]

[1]Earth Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

[2]School of Environment and Natural Resources, Ohio State University, Columbus, Ohio

[3]Forest Ecology and Management, Sveriges Lantbruksuniversitet Fakulteten for Skogsvetenskap, Umeå, Sweden

[4]Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark

[5]Faculty of Science, Earth and Climate, VU Amsterdam, Amsterdam, Netherlands

Correspondence
Alexa Hinzman, Earth Sciences,
Vrije Universiteit Amsterdam, Amsterdam,
Netherlands.
Email: a.m.h.hinzman@vu.nl

Abstract

The Arctic is warming at an unprecedented rate. We hypothesis that as seasonally frozen soils thaw and recede in extent as a response to this warming, flow path diversity and thus hydrologic connectivity increases. This enhanced hydrologic connectivity then increases the non-linearity of the storage-discharge relationship in a catchment. The objective of this study is to test this hypothesis by quantifying trends and spatio-temporal differences in the degree of linearity in the storage-discharge relationships for 16 catchments within Northern Sweden from 1950 to 2018. We demonstrate a clear increase in non-linearity of the storage-discharge relationship over time for all catchments with 75% showing a statistically significant increase in non-linearity. Spring has significantly more linear storage-discharge relationships than summer for most catchments (75%) supporting the idea that seasonally frozen soils with a low degree of hydrological connectivity have a linear storage-discharge relationship. For the period considered, spring also showed greater change in storage-discharge relationship trends than summer signifying that changes in recessions are primarily occurring during the thawing period. Separate storage-discharge analyses combined with preceding winter conditions demonstrated that especially cold winters with little snow yielded springs and summers with more linear storage-discharge relationships. We show that streamflow recession analysis reflects ongoing hydrological change of an arctic landscape as well as offering new metrics for tracking change across arctic and sub-arctic landscapes.

KEYWORDS

arctic hydrology, recession analysis, seasonally frozen soil, storage-discharge, thaw

1 | 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 catchment: snow and rainfall precipitation distributions, vegetation coverage, groundwater storage, permafrost and thawing depth (Hinzman et al., 2005; Hinzman, Yoshikawa, & Kane, 2005). Permafrost and seasonally frozen soils are of specific concern as sentinels of long-term change in the Arctic (Jorgenson et al., 2010). Permafrost is defined as soil, rock or other natural material that has been frozen for two or more consecutive years (van Everdingen & Association, 1998). This definition means that permafrost differs from soils that are frozen for less than 2 years or that thaw every summer, which are considered 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 soils 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 (Zhang, Barry, Knowles, Heginbottom, & Brown, 2008), understanding how seasonally frozen soils in permafrost 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 and Kurylyk (2016) reviewed multiple arctic water flow models and showed that while groundwater exchange and subsurface connectivity are predicted to increase locally, model results are inconclusive on how surface connectivity and river flow dynamics will change across spatial scales. Hinzman, Yoshikawa, and 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, but rather several interacting changes that exacerbate other changes to create complex responses that 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, help identify dominant processes, and support building reliable models that can project change trajectories into the future. Although still considered sparse, river discharge is the most commonly available hydrologic observation throughout the Arctic (Laudon & Sponseller, 2018) and contains integrated signals of catchment processes affected by Arctic warming (Bring et al., 2016). In this study, we aim to quantify long-term trends in how catchments release water (i.e., trends in catchment 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 et al., 2009; Lyon & Destouni, 2010; 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 and 1.3 cm/year 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 non-linear (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, Lyon, Teuling, Laudon, & van der Velde, 2019; Walvoord & Kurylyk, 2016). Frozen soils are found to seasonally alter the hydrological connectivity within catchments by redirecting water through shallow (above the frozen layer) and deep (below the frozen layer) flow paths 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 is the hydrologic response of Arctic and sub-Arctic catchments impacted as the climate warms and the extent of frozen soils decreases? Following up on the study of Ploum et al. (2019), we anticipate that under thawed conditions deep groundwater, shallow groundwater and overland flow paths all contribute to discharge. Contrarily, under frozen topsoil conditions, shallow flow paths dominate although deep groundwater can still contribute to a lesser extent. This increase in flow path diversity is assumed to occur under a warming climate over both the long-term (i.e., as permafrost thaws and summer active layer increases) and on a seasonal timescale (i.e., as seasonally frozen soil thaw starts earlier in the spring occurs). Previous studies have shown that when catchments become wet and the diversity of flow paths increases, increasingly non-linear relationships between storage and discharge are observed (Brutsaert & Nieber, 1977).

Based on previous studies, our hypothesis is that as seasonally frozen soils thaw and recede in extent, flow path diversity and therefore hydrologic connectivity increases, which in turn increases the non-linearity of the storage-discharge relationship. In this current study, our objective is to test this hypothesis by quantifying trends and spatio-temporal differences in storage-discharge relationships for 16 catchments within Northern Sweden from 1950 to 2018. Northern Sweden has had strong temperatures increases from the start of the 1800s to present day of almost 0.1°C/decade, with a cooling period occurring between 1940s and 1970s (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.

2 | METHODS

2.1 | Concepts

2.1.1 | Recession analysis

Recession analysis is a well-established hydrologic method to examine storage-discharge relationships of catchments and 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. Under the assumptions of a unique relationship between storage and discharge and a closed water balance, recession curves quantify the storage-discharge relationship (Brutsaert, 2008; Kirchner, 2009).

Recession curves are determined by fitting a non-linear storage-discharge relationship to falling limbs of hydrographs during periods without precipitation and evapotranspiration. These are periods when changes in discharge reflect changes in catchment water storage (Brutsaert & Nieber, 1977; Kirchner, 2009; Ploum et al., 2019). Traditionally, the rate of discharge decline during the recession, namely *dQ/dt* [mm/d/d], is defined as:

$$\frac{dQ}{dt} = -Q\frac{dQ}{dS} \approx -\alpha Q^{\beta}, \tag{1}$$

where Q is discharge [mm/d], dQ/dS is the sensitivity of discharge [d^{-1}] to changes in storage (Kirchner, 2009). If discharge data for the recession periods are plotted as $\log\left(-\frac{dQ}{dt}\right)$ against $\log(Q)$, then α represents the intercept [$mm^{1-\beta}d^{\beta-2}$] and β represents the slope of a straight line fitted to the data [–], referred hereafter as the recession curve slope. The recession curve analysis technique has been applied to many regions to help improve understanding the relationship between groundwater and river discharge (Brauer, Teuling, Torfs, & Uijlenhoet, 2013; Dralle, Karst, Charalampous, Veenstra, & Thompson, 2017; Lyon et al., 2015) and as such can also be used to better understand the response of the storage-discharge relationship to climate change (Ploum et al., 2019; Shaw & Riha, 2012; Wrona et al., 2016).

Here, we extend Equation (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 at the cost of a higher data requirement:

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

where P is precipitation [mm/d] and E is evapotranspiration [mm/d].

2.1.2 | Conceptualizing storage-discharge relationships

Recession curve slopes can be conceptually interpreted as a measure of hydrologic connectivity as illustrated by a series of sand-filled buckets (Figure 1). A catchment with one dominant flow path where discharge increases exponentially with storage behaves similar to a bucket with a single spigot representing a linear reservoir ($\beta \approx 1$) (Figure 1). Observed examples of such linear reservoirs are catchments with a deeply incised rivers flowing 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 an unconfined aquifer, both the pressure as well as the saturated thickness control flow (Troch et al., 2013), which can be represented by a bucket with multiple evenly distributed and equally sized spigots (analogous to flow paths). Here, flow not only depends on the pressure exerted by storage on the spigots but also by the number of spigots. Such a sand-filled bucket behaves as a non-linear reservoir (specifically with $\beta = 1.5$). Finally, we can consider the case of a bucket with increasing density of spigots or increasing size of spigots towards the surface. Such a system will have $\beta > 1.5$ as has been seen in many natural systems (e.g., Kirchner (2009), Karlsen et al. (2019), Jachens, Rupp, Roques, and Selker (2020), and Brauer et al. (2013)). In these systems, as catchments become wetter, lower order streams are activated and start to contribute to the catchment's discharge. Thusly, each spigot from the bottom upward could be interpreted as a lower stream order with a larger area starting to contribute. A special case is when the resistance of the spigots decreases exponentially towards the surface yielding an exponential reservoir ($\beta = 2$) as is frequently observed in relatively flat catchments (e.g., Bogaart et al. (2016) and Brauer et al. (2013)). Reservoirs where the resistance declines hyperbolically towards the surface yield $\beta > 2$ (Brutsaert & Nieber, 1977; Kirchner, 2009; Troch et al., 2013).

With the understanding that potential flow paths are disrupted by frozen soils, we use recession curve analyses to understand how declining permafrost extent and shifts in extent of seasonally frozen soils may have affected river flow and specifically the non-linearity of the storage-discharge relationship (e.g., recession curve slope). Therefore, we set out to identify temporal and seasonal changes in recession curve slopes (β) which we compare to expected changes in recession curve slopes caused by a declining extent of frozen soils based on the conceptualizations in Figure 1.

2.2 | Study sites

Our study sites are situated in Northern Sweden. The 16 catchments were chosen because they (a) have presumed permafrost presence in the past and present Brown et al., 1997; Gisnås et al., 2017; Zhang et al., 1999), (b) have widespread occurrence of seasonally frozen soils and (c) have no current or past known obstructions of the waterways by human intervention (Sjöberg et al., 2013). Land cover in Northern Sweden is mainly forests, which are used for logging. Since 1903 there has been strict forest management across Northern Sweden to insure restoration of the forests (Anderberg, 1991), indicating no dramatic change in land cover over the past century.

For the catchments considered, Övre Abiskojokk, Kaalasjärvi, Tängvattnet and Niavve are the steepest (Table 1). Övre Abiskojokk,

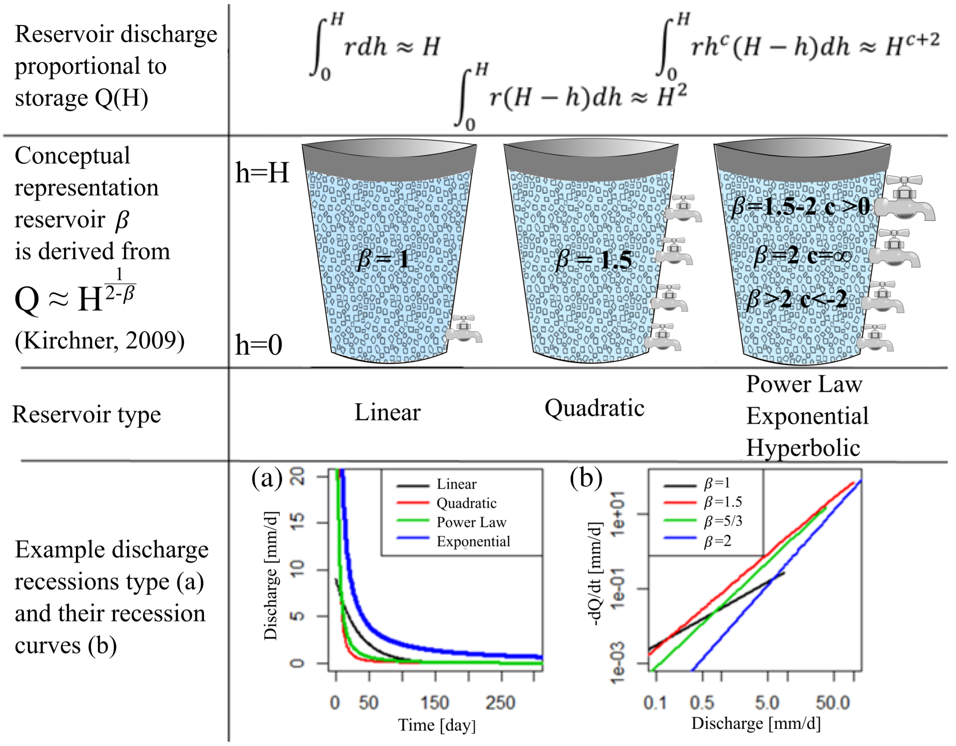

FIGURE 1 Flow path representation of recession slope. *H* is water level in the reservoir, *h* is the integration variable, *r* represents the flow resistance of a spigot and *c* is the power with which r decreases with increasing H

TABLE 1 List of Swedish study catchments summary: Dataset timing, average slope, average elevation, outlet location and catchment area

Catchment	Dataset years	Average elevation (masl)	Average slope (m/m)	Latitude (°)	Longitude (°)	Area (km^2)
Karesuando	1972–2017	581	0.064	68.45	22.48	5,960
Mertajärvi	1959–2017	419	0.038	68.37	22.17	391
Övre Abiskojokk	1985–2017	951	0.198	68.36	18.78	566
Lannavaara	1965–2015	588	0.048	68.04	21.98	3,856
Kaalasjärvi	1957–2010[a]	859	0.176	67.74	20.02	1,473
Junosuando	1974–2017	579	0.088	67.43	22.55	4,348
Killingi	1975–2018	805	0.128	67.52	20.28	2,346
Tärendö	1984–2017	611	0.092	67.13	22.62	13,000
Niavve	1951–2017	836	0.166	66.88	18.22	1718
Karats	1951–2018	636	0.081	66.65	18.83	1,174
Stenudden	1965–2017	792	0.116	66.55	17.76	2,420
Laisvall	1989–2017	793	0.106	65.99	17.2	1774
Gauträsk	1961–2010[a]	845	0.121	65.93	16.3	1,263
Tängvattnet	1965–2017	724	0.14	65.83	14.9	195
Solberg	1965–2015	784	0.107	65.75	15.39	1,084
Skirknäs	1980–2015	759	0.114	65.7	16.25	418

[a] Signify catchments with data gaps.

Kaalasjärvi, Killingi and Gauträsk have higher than average elevations, which makes Övre Abiskojokk and Kaalasjärvi the two most mountainous catchments in this study (Table 1). Karesuando, Mertajärvi, Lannavaara and Junosuando have the lowest average elevations with Mertajärvi being the lowest. 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 catchments. Tärendö and Junosuando stretch into the eastern part of the country, characterized with lower elevations (Figure 2). Tärendö is the largest catchment, stretching close to the Gulf of Bothnia (Sjöberg et al., 2013), followed by Karesuando and Junosuando. The smallest

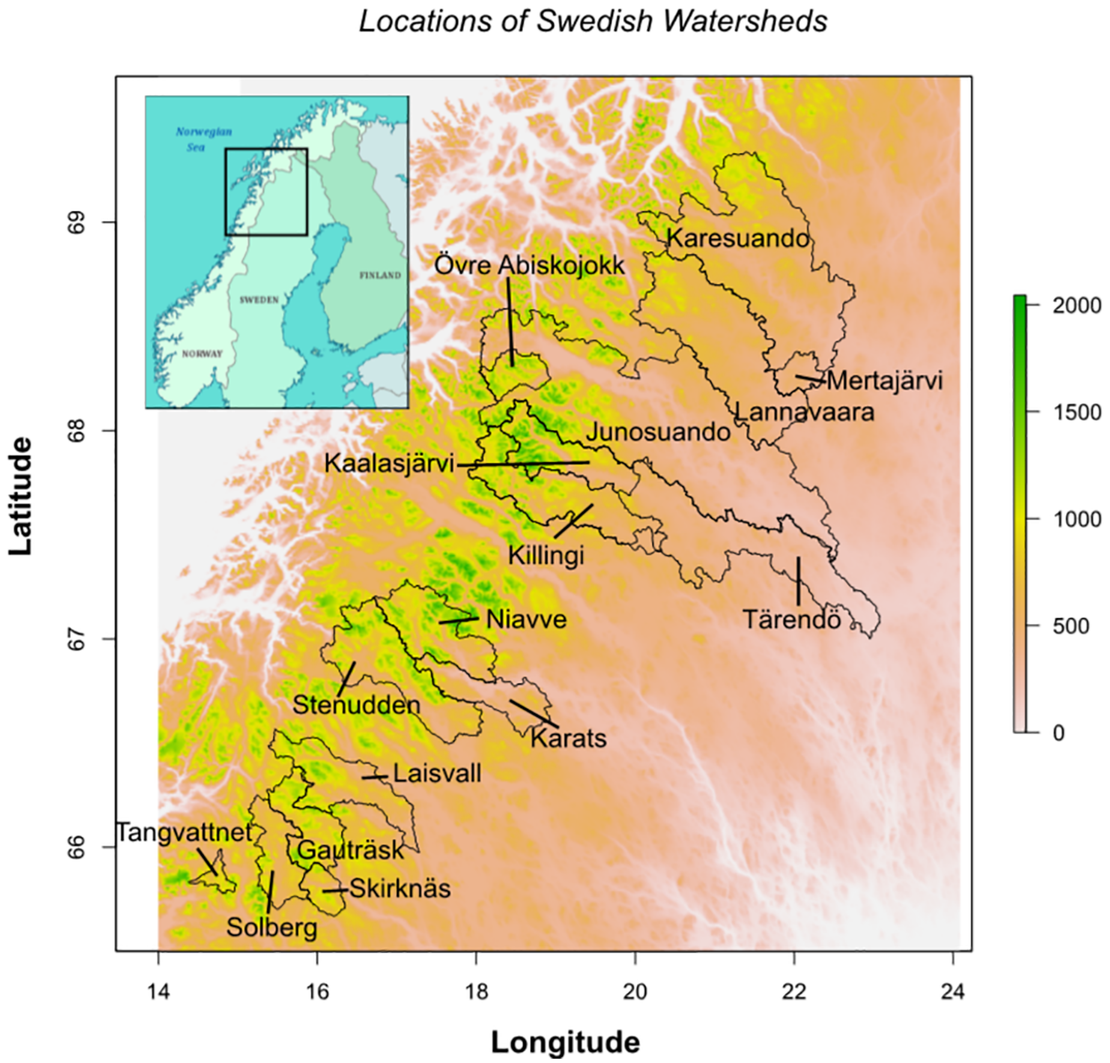

FIGURE 2 Map of Northern Sweden study catchments

catchments are Tängvattnet, Skirknäs, Mertajärvi and Övre Abiskojokk (Table 1). Mertajärvi is nested in Karesuando, Övre Abiskojokk flows into Junosuando and lastly, Kaalasjärvi and Killingi are nested in Tärendö. The remaining catchments are not nested.

2.3 | Discharge, rainfall, temperature and snow depth data

Observed discharge and meteorological data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI), (SHMI, 2018) for the stations listed in the supplementary information (Table S1). These data are derived from public domain online repositories and range from 67 to 32 years in length with an average of 46 years. Gauträsk has a dataset gap of 6 years and Kaalasjärvi has two dataset gaps of 10 and 3 years. For metrological data, daily measurements of precipitation, maximum and minimum temperatures and snow depth were used. Maximum and minimum temperatures were used to roughly estimate daily potential evapotranspiration with the Priestley-Taylor approach (Priestley & Taylor, 1972). For catchments where discharge data are collected separately from meteorological data, the geographically closest meteorological station was used (see the supplementary (Table S1) for the names of stations used for each catchment). The distance between meteorological and discharge stations was on average 14 km and the maximum did not exceed 45 km. No correction was done for elevation differences between meteorological stations and discharge stations.

Snow depth (*Sd [mm]*) was irregularly documented in the catchments by SMHI. For periods when direct observations were not available or were very sparse, the snow depth was roughly approximated by using the recorded data in combination with sums of winter precipitation during freezing conditions (i.e., 0°C and below).

$$Sd_i = Sd_{i-1} + 10 * P(t) * \Delta t \text{ for } T \leq 0^\circ\text{C} \tag{3}$$

$$Sd_i = Sd_{i-1} + (-18 * T(t) - 8 * P(t))) * \Delta t \text{ for } T > 0^\circ\text{C} \tag{4}$$

where T [°C] is temperature, P [mm/d] is precipitation, Δt [d] is a time step of 1 day and *i* is the day of the year. We used a snow density of 10 [–] mm snow per mm water roughly following Marks, Winstral, Reba, Pomeroy, and Kumar (2013). If temperature was above freezing, we assumed a snow melt of 18 [mm/day/°C] mm of snow per day per degree above zero and 8[–] mm of additional snow melt per day per mm of rainfall. These values fall in the range of values reported for other Scandinavian catchments by Akanegbu, Marttila, Ronkanen, and Kløve (2017). For the purpose of this current study, it was not necessary to have exact estimates of snow depth. Rather, our simple approximation needs to yield a rough indication of the end of the spring season (i.e., the period of snowmelt) and to be useful for identifying snow rich and snow poor years.

2.4 | Recession curve slope (β)

To determine the degree of non-linearity of the storage-discharge relationship (β), we selected hydrograph recession observations when Q was larger than 0.5 mm/d in order (1) to focus on the wetter periods when we expect a larger effect of frozen soil layers and (2) to exclude low flows with typically a large effect of evaporation and a large measurement uncertainty. We also added a condition that hydrograph observations would only be included when both precipitation and evapotranspiration were less than half of Q. Data were excluded during the first 3 days after a precipitation event to avoid errors in monitoring the timing and extent of precipitation that could influence the catchment response. β is determined as the slope of a linear line fitted directly to the selected data points in a plot in which the x-axis corresponds to log(Q) and the *y*-axis to the full left side of Equation (2).

2.5 | Season definitions

We analysed spring and summer recessions separately. The onset of spring was defined based on a degree day methodology approach proposed by Ploum et al. (2019). Mean daily temperatures were summed with cumulative sums below zero reset to zero. The first day the cumulative summed temperature exceeded 15 degree days was defined as the onset of spring. The end of spring and the beginning of summer was defined as 31 days after the last snow had melted at the nearest meteorological station following Ploum et al. (2019). Ploum et al. (2019) examined different lag times between 21 and 31 days and found that the spring recession curve slope was not sensitive to such changes in the end of spring definitions. Therefore, we chose the larger lag time of 31 days to increase the number of recessions observations during the spring period. The end of summer was determined by three consecutive days with equal or below 0°C average temperatures (Figure 3a).

2.6 | Analyses approach

To identify and quantify the potential effects warming and a subsequent decline in frozen soil extent may have had on recessions, we performed the following four analyses that connect to four hypotheses/expectations:

1. Temporal trends in recession curve slopes over time. We expect increasingly non-linear storage-discharge relationships (i.e., positive trends in β) as frozen soils recede in a warming climate.

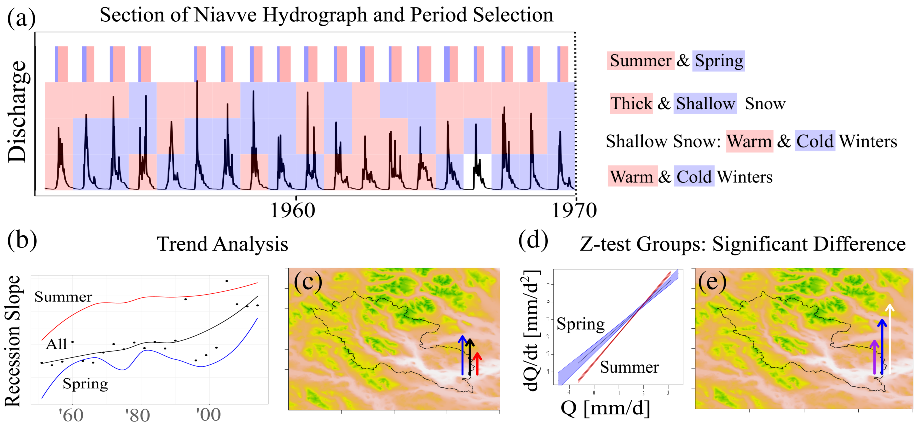

FIGURE 3 Example of analysis steps for catchment data separation and test results. (a) A section of the Niavve hydrograph with four different data selections, from top to bottom: spring and summer, thick and shallow snow, warm and cold winters during shallow snow, and warm and cold winters. The colour of the selected periods denotes the hypothetical difference in recession curve slope. Red indicates periods that will have more non-linear recession curve slopes when compared to the blue periods. (b) Temporally continuous periods are analysed over time with the Mann Kendall and Theil Sen tests. (c) A map of Niavve with arrows indicating the trend over time, spring (blue), all seasons (black) and summer (red). (d) A graph of spring and summer recession curves with confidence intervals. (e) A map with arrows to show the differences between periods, spring and summer (purple), warm and cold winters (black), thick and shallow snow (white) and shallow snow: cold and warm winters (green). Negative arrows indicate results contrary to our hypotheses. Thin arrows are for insignificant results in both (c) and (e)

Trends in recession curve slope are determined from non-overlapping 3-year periods. Three-year periods ensure enough data points within each period for robust estimates of the recession curve slope, and enough time periods for robust estimates of trends in recession curve slope. 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).

2. Recession for spring and summer periods, separately (Figure 3a). During spring periods, we expect that the hydrologic effects of frozen ground is stronger than during summer periods. Therefore, we expect that spring periods have a lower recession curve slope (more linear storage-discharge relationship) than summer periods.
   Recessions were grouped into spring and summer recessions for each catchment. The two-sample *z*-test (Cohen, Cohen, West, & Aiken, 2003) was used to test whether the recession curve slopes were significantly different between both groups.
3. Temporal trends in spring and summer recession curve slopes. The aim was to identify which season contributed most to the observed yearly trends (i.e., Analysis 1 above). If a declining extent of frozen soils is the dominant driver for a change in recession curve slopes, we expect spring to show a greater change than summer.
   This analysis followed the same method as for the trend over time analysis described in Analysis 1 (above) but was applied separately for spring and summer periods (Figure 3b).
4. Frozen soil influence on recession curve slopes. We expect recessions following winters with deeply frozen soil to have a more linear recession curve slope than those following shallow frozen soil winters.

The depth of seasonal freezing depends on winter air temperatures and the thickness of the insulating snow cover (Zhang, 2005). As such, we considered three proxies for frozen soil depth: average winter temperature, winter snow depth and a combination of both. The soil potentially freezes deeper during cold winter. Therefore, it potentially takes longer for frozen soil to thaw during spring after a cold winter compared to springs after warmer winters (Lawrence & Slater, 2010). Hence, recession curve slopes during springs following cold winters are expected to be more linear compared to the warm winters. We split winters into two equally sized groups: cold winters and warm winters, based on the average winter temperatures (Figure 3a). We then used the two-sample *z*-test to test for significant differences in recession curve slope between both groups. We performed the same analysis for snow depth. Winters with shallow snow are expected to have more soil frost and therefore we expect that springs following shallow snow winters have a more linear recession curve slope. Winters were split into two equally sized groups based on the maximum winter snow depth and again the two-sample *z*-test was used to test for significant differences between both groups. As a last proxy for frozen soils we combined winter temperature and snow depth recognizing that soils freeze during periods when both snow depth and temperatures are low. We expect that recession curve slopes after such winters are more linear. The insulation effect of snow was found to peak at about 40 cm (Zhang, 2005). To isolate this insulating effect, we calculated the cumulative winter temperature for the days with a snow depth below 20 cm, which can be considered a shallow snow pack. The years are divided into two groups to create "shallow snow: cold winter" years and "shallow-snow: warm winter" years (Figure 3a). We again used the two-sample *z*-test to test for significant differences in recession curve slope between both groups (Figure 3d).

2.7 | Spatial visualization

To visualize the spatial pattern of changing recession curve slopes we plotted the trend magnitude of change in summer, spring and year-round recession curve slopes as an arrow at the catchment outlet (example in Figure 3c). Upward arrows indicate an increase in non-linearity with time and downward arrows a decrease in non-linearity with time. Similarly, we plotted the differences in recession curve slopes between warm and cold winter groups, thick and shallow snow depth groups, and "cold-winter-during-shallow-snow" and "warm-winter-during-shallow-snow" groups as an arrow (example in Figure 3e). Upwards arrows indicate a result anticipated by our hypotheses. Downward arrows indicate a result contradicting our hypotheses. Bolded arrows indicate significance, if not bolded, the result is not significant.

3 | RESULTS

3.1 | Trend over time

Our analyses demonstrated a widespread increase in non-linearity of recessions in Northern Sweden year-round (Figure 4). Ten of sixteen catchments showed 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 catchment had a significant negative trend for both trend tests. Overall, fourteen of the sixteen catchments had a positive trend, and twelve catchments had a significant positive trend of the recession curve slope for the Theil Sen test (Table 2). On average, the trend of the recession curve slopes increased 0.006 Y^{-1} with mostly linear recessions (β = 0.8–1.3) in the period 1950–1970 increasing towards more non-linear recessions (β = 1.3–2.2) during this period 2010–2018.

Mertajärvi, Övre Abiskojokk, Kaalasjärvi, Tärendö, Niavve, Karats, Stenudden, Gauträsk, Tängvattnet and Solberg had statistically significant positive trends in recession curve slope for both statistical tests. It was not until the 1980's and 1990's when recession curve slopes started to increase (Figure 4). Stenudden, Niavve and Karats are geographically close and had similar trends in recession curve slopes. Of these, Karats showed the strongest increase in non-linearity during the last decade (Figure 4). Solberg, Skirknäs, Gauträsk and Tängvattnet

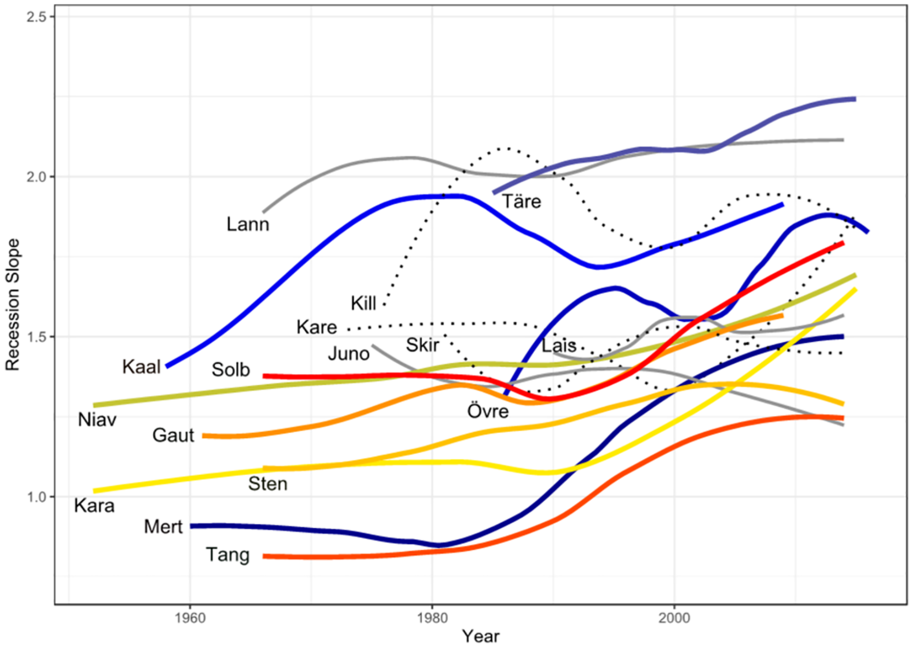

FIGURE 4 Trend of recession curve slopes over time for all catchments. Catchments demonstrating statistically significant recession curve slopes increases for both Theil Sen and Mann Kendall tests are coloured. The catchments are coloured from North to South, blue to red. Black, dotted lines are non-significant, and grey lines are significant only for the Theil Sen test. The lines were created using the LOESS method

TABLE 2 Results of overall trend, seasonal recession comparison and seasonal trend comparison

		Trend[Y^{-1}] analysis #1 & #3			Z-test analysis #2	
Catchment	Overall β	Year-round	Spring	Summer	Spring β	Summer β
Karesuando	1.56	−0.001	−0.006	0.005	1.05	**1.66**
Mertajärvi	1.24	0.016‡†	0.010‡†	**0.024**‡†	1.49	1.55
Övre Abiskojokk	1.68	0.008‡†	0.013	0.010‡	1.33	**1.76**
Lannavaara	2.05	0.006‡	−0.005‡	0.001	1.53	**2.29**
Kaalasjärvi	1.86	0.007‡†	0.001	0.011‡	1.08	**2**
Junosuando	1.36	−0.004‡	0.019	0.012‡	1.57	1.75
Killingi	1.88	0.003	**0.017**‡	0.006‡	1.2	**1.77**
Tärendö	2.1	0.011‡†	**0.025**‡	0.015‡	0.8	**2.26**
Niavve	1.48	0.004‡†	0.001	0.004‡	1.26	**1.66**
Karats	1.3	0.003‡†	**0.028**‡†	0.006‡†	0.73	**1.18**
Stenudden	1.27	0.006‡†	**0.028**‡	0.012‡†	1.16	1.23
Laisvall	1.51	0.006‡	−0.032‡	0.001	1.45	**1.89**
Gauträsk	1.39	0.007‡†	0.003	0.002	1.21	**1.41**
Tängvattnet	1.08	0.012‡†	**0.018**‡†	0.006‡†	1.11	1.03
Skirknäs	1.44	0.002	−0.006	0.004	1.08	**1.91**
Solberg	1.48	0.007‡†	0.007‡	0.003	0.74	**1.28**

Note: For overall and seasonal trends, if the trend is significant ($p < .05$) for Theil Sen, it will be denoted by an "‡," if it is significant ($p < .05$) for Mann Kendall, then it will be denoted as "†." The greatest change of trend between spring and summer is bolded, only if both trends are significant. For the *z*-test comparing spring to summer, the more non-linear recession curve slope is bolded, only when the difference is significant. The catchments are ordered from north to south.

are also geographically close (Figure 2). Tängvattnet exhibited the lowest recession curve slopes of the four and while the recession curve slope increased with time. Tängvattnet started with a recession curve slope under 1.0 and it did not increase above 1.0 until 1995. Junosuando exhibited the only significant negative trend of all the catchments (significance only for the Theil Sen test). A likely reason could be that Junosuando's gauging site was originally situated upstream of a river bifurcation, but the bifurcation has moved upstream of the site. These results follow our hypothesis (Analysis #1) that in a warming climate with a reduction of frozen soil extent and an increase in flow pathways contributing to river discharge, storage discharge relationship become more non-linear.

3.2 | Spring and summer difference

Our second hypothesis (Analysis #2) that spring recessions are more linear than summer recessions was also substantiated. Twelve out of sixteen catchments had more linear spring storage-discharge relationships and more non-linear summer storage-discharge relationships (Table 2). The catchments with significant results are indicated with thick purple arrows in Figure 5b. Mertajärvi, Junosuando, Stenudden and Tängvattnet were the catchments without a significant difference between summer and spring periods.

The Mann Kendall test yielded six catchments with a significant trend in the recession curve slope for the summer (Analysis #3): Mertajärvi, Kaalasjärvi, Stenudden, Killingi, Niavve and Tängvattnet (Table 2). Thirteen trends in summer recession curve slope were significant for the Theil Sen estimator with only Junosuando having a negative trend. The Mann Kendall test yielded only one catchment with a significant trend in spring recession curve slope: Tärendö. Nine trends in spring recession curve slope were determined to be significant with the Theil Sen estimator, seven were positive (Figure 5a).

When comparing the two seasonal periods (Analysis #3), summer had the greater number of significant trends in recession curve slope, but the magnitude of increasing trends in recession curve slope were generally larger during spring (Figure 5a). In Killingi, Tärendö, Karats, Stenudden and Tängvattnet, (Figure 5a) yearly trends in recession curve slopes seem dominated by spring changes; only Mertajärvi exhibited dominant summer change. For all other catchments, a significant trend in recession curve slope could not clearly be attributed to either season but was driven by both periods.

3.3 | Attribution to winter conditions

Twelve of sixteen catchments had recession curve slopes closer to linearity for colder winters than for warmer winters as shown in Table 3. Ten of those twelve catchments had a significant difference between cold and warm winters. None showed significant higher non-linearity in cold winters compared to warm winters. These results follow our hypothesis (Analysis #4) that years following warm winters exhibit more non-linear storage-discharge relationships. Our results were inconclusive, however in regards to differences in recession curve slopes between thick and shallow snow cover: six catchments had a significant higher recession curve slope during shallow snow cover, while five catchments had a significant lower recession curve slope during shallow snow cover. Five catchments had no significant difference that could be related to snow cover. There was geographical clustering of the significant catchments (Table 3, Figure 5b); Övre Abiskojokk, Kaalasjärvi, Killingi and Tärendö (part of the same mountain range) had a higher recession curve slope when snow cover was thick. From our results, we cannot conclude how a

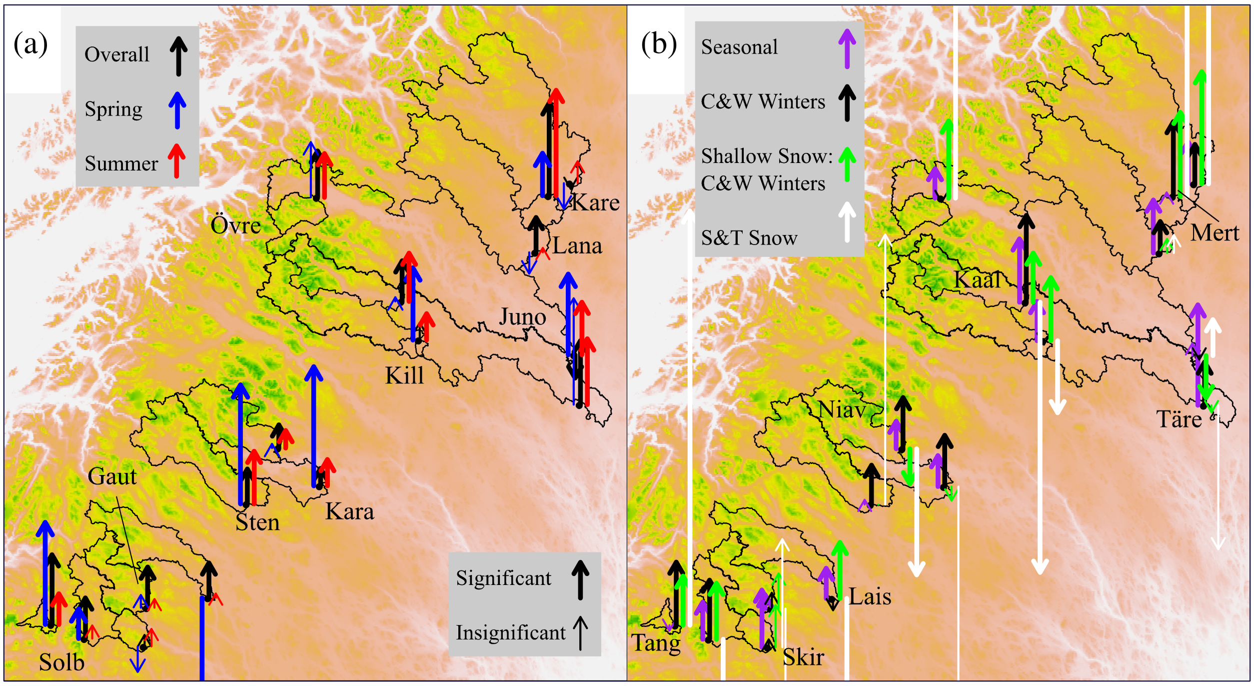

FIGURE 5 (a) Trend results of all catchments. The arrows represent change in overall trend (black), spring trends (blue) and summer trends (red). Trend arrow length indicates the overall change in recession curve slope trend. Thick arrows are for significant results. (b) *Z*-test results for all catchments. The arrows represent the difference between seasons (purple), cold and warm winters (black), cold and warm temperatures during shallow snow periods (green) and shallow and thick snow packs (white). Thick arrows are for significant results. Upward *z*-test arrows indicate results that concurred with our hypotheses

TABLE 3 Analysis #4 Warmer and colder winter recession curve slope results along with cold and warm temperatures during shallow snow depth (below 20 cm) for all seasons combined

Catchment	Cold winter β	Warm winter β	Shallow snow β	Thick snow β	Shallow snow cold winter β	Shallow snow warm winter β
Karesuando	1.52	**1.62**	1.49	**1.61**	1.47	**1.63**
Mertajärvi	1.14	**1.33**	1.1	**1.36**	1.18	**1.3**
Övre Abiskojokk	1.7	1.69	1.59	**1.73**	1.64	**1.75**
Lannavaara	2	**2.08**	2.05	2.06	2.04	2.06
Kaalasjärvi	1.67	**1.89**	**1.93**	1.78	1.83	**1.9**
Junosuando	1.36	1.35	1.35	1.37	**1.39**	1.33
Killingi	1.89	1.88	1.89	1.85	1.83	**1.92**
Tärendö	2.05	**2.16**	**2.14**	2.06	2.09	2.08
Niavve	1.4	**1.53**	**1.51**	1.44	1.5	**1.45**
Karats	1.21	**1.34**	**1.37**	1.21	1.3	1.28
Stenudden	1.21	**1.31**	1.18	**1.33**	1.28	1.28
Laisvall	1.53	1.5	**1.55**	1.48	1.47	**1.55**
Gauträsk	1.28	1.32	1.41	1.36	1.36	1.41
Tängvattnet	0.98	**1.14**	0.92	**1.15**	1.01	**1.08**
Skirknäs	1.42	1.44	1.41	1.47	1.4	1.46
Solberg	1.39	**1.54**	**1.52**	1.45	1.43	**1.51**
Up to 1990						
Mertajärvi	0.95	0.91	0.94	0.94	0.99	1
Niavve	1.34	1.36	1.37	1.34	1.34	1.34
Karats	1.09	1.08	1.11	1.05	1.26	1.24
Tängvattnet	0.8	0.83	0.83	0.81	0.84	0.85

Note: The catchments are ordered from north to south. When the difference is significant, the larger recession curve slope is bolded.

catchment's recession curve slope will react to a change in snow depth (Analysis #4). As soil frost is controlled by both winter temperature and snow insulation, our final soil frost indicator was the cumulative winter temperatures during shallow snow depth conditions (Analysis #4). This frozen-soil proxy yielded consistent results. Ten catchments had significant differences between the cold and warm winters during shallow snow periods. Nine significant catchments had increased non-linearity in recession curve slopes during warm winters than cold winters, echoing our anticipated results for warm and cold winters.

Because many of the warmer winters occurred within recent years, it is possible that our results are due to a general increase in temperatures rather than winter temperature differences between individual years. Therefore, we wanted to test if winter temperature also impacted the recession curve slopes for the period leading up to 1990, when there was no clear trend in recessions-curve slope for most catchments (Figure 4). In that period, for the four catchments with the longest observational records, (Mertajärvi, Karats, Niavve and Tängvattnet), we found no significant difference for any of the analyses for any catchment. We should mention that there are less data if we limit the analyses to pre-1990, which increases uncertainty and decreases the probability of significant differences.

4 | DISCUSSION

4.1 | Trend in recession curve slope

Catchments with data starting in the 1950s (Karats, Mertajärvi, Gauträsk, Niavve and Kaalsjärvi) had yearly average recession curve slopes between 0.75 and 1.25, but have significantly increased to values around 1.5 through the present, with the exception of Kaalsjärvi which had a recession curve slope of 1.4 in the 1950s and close to 2.0 in the 2010s (Figure 4). We find recession curve 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). Previous studies have indicated that catchments analysed with different regression methods will result in different recession curve slope values (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). However, the direction of differences between catchments and between periods of the same catchment 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 changes (Silfverstrand, 2019), and SHMI continually checks for errors in discharge data to insure accurate observations. Therefore, the observed changes in recession curve slopes come from other aspects, such as land cover change, or thawing permafrost. If soil frost thaw is truly causing a change in recession curve slope, it is mainly by the increasing thickness of the active layer as the soil thaws. This increasing active layer thickness causes a larger diversity in flow paths contributing to stream discharge during a hydrograph recession as the landscape moves from wet to dry conditions. In addition to significant differences in seasonal recessions found by Karlsen et al. (2019) and Ploum et al. (2019), our research contributes with showing significant increasing non-linearity of recession behaviour since 1950.

Considering the year-round trend analysis, ten trends in recession curve slopes are positive and significant for both statistical tests, while no trends are negative and significant for both statistical tests. Sjöberg et al. (2013) found for the same catchments that late summer recession intercept (α in Equation (1)) 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 catchments. Lyon and Destouni (2010) and Sjöberg et al. (2013) focused on late summer for recession analysis and assumed a recession curve slope of 1. 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 behaviour (β = 1) cannot be assumed. Moreover, we showed that the effects of a warming Arctic on river discharge are more pronounced during spring conditions, than during summer conditions by showing that the omnipresent trend of increasing non-linearity in storage-discharge relationships (increasing slopes in the recession curve) are potentially caused by changes in spring.

Groundwater flow through thawing soils is a complex process. Arctic catchments 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 corroborating evidence that recession curve 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 catchments while under wet conditions water is released faster. In times when the water flow paths are filled, usually during snowmelt or periods of continued precipitation when the landscape is by-and-large saturated, overland flow will contribute to discharge along with the usual groundwater flow, creating potentially even higher discharge peaks then under periods with extensive permafrost spatial extents. More non-linear storage-discharge relationships likely also make river peak flows more unpredictable as uncertainties in precipitation and/or snowmelt inputs propagate more strongly into discharge under such conditions. 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 catchment properties that underlie storage-discharge relationships.

4.2 | Seasonal recession curve slope

Ploum et al. (2019) explored storage-discharge relationships for Övre Abiskojokk, a catchment included in our study, and concluded recessions slopes were likely influenced by seasonal soil frost. Ploum et al. (2019) hypothesized that summer recessions slopes would be larger than spring recession curve 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 recession curve slopes than in spring in the boreal catchment Krycklan. With 15 more catchments, we also find storage-discharge relationships with consistently higher recession curve 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 catchment increases from spring to summer due to thawing soils. The more non-linear storage-discharge relationship in summer compared to spring implies that when conditions are wet and storages full, a more immediate and strong response of discharge to additional rainfall is expected in summer compared to spring. However, due to the large snowmelt volume 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 different.

4.3 | Trends in spring and summer recession curve slope

Spring recession curve slopes had stronger trends 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 12 catchments, summer has the higher recession curve slope (i.e., more non-linear) (Analysis #2), but over time (Analysis #3), we see that spring is undergoing a greater change than summer (Table 2). Of the six catchments with significant differences, five have higher trends in spring. Frampton, Painter, Lyon, and Destouni (2011) suggested that thawing soils lead to increasing flow path 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 seasonally frozen soils have already thawed in spring and are no longer affect discharge during summer. However, when permafrost is omnipresent within the catchment and permafrost is slowly disappearing, summer recessions may be affected more strongly than spring recession when soils are still primarily underlain with a frozen layer.

4.4 | Attribution to winter conditions

For the region in this study, there has been increasing winter temperatures since the start of 1900 (Luterbacher, Dietrich, Xoplaki, Grosjean, & Wanner, 2004). With no exceptions, all 10 catchments with significant differences between cold and warm winters have a higher recession curve slope following warm winters than cold winters. Therefore, it can be concluded that there is a significant increase in non-linearity of recession curve slopes for warmer winters relative to colder winters for these sub-arctic catchments (Figure 5b). Our hypothesis was that this pattern is because warmer winters have a shallower frozen soil layer, which thaws quicker than after colder winters with a deeper frozen soil layer. However, we could not confirm this when examining data before 1990 for the four catchments with the longest records. St. Jacques and Sauchyn (2009) also found evidence of winter air temperatures affecting streamflow. They suggested that this effect is caused by thawing soils that increase infiltration and subsequent subsurface flow of water to the stream.

Payn, Gooseff, McGlynn, Bencala, and Wondzell (2012) found that the correlation between subsurface flow paths and surface attributes decreased during recession because subsurface structures gain more influence on the subsurface flow paths during low flows. Subsurface structures can be many things, including permafrost, the geologic features of the catchment, and seasonally frozen soil. Moreover, these subsurface structures can be dynamic and indirectly related to surface features. Snow, for example, is an important and variable surface feature for impacting the dynamics of frost depth as it insulates the ground from heat loss (Hirota et al., 2006). Catchment-scale seasonal soil freezing is a complex process that cannot easily be captured by just a simple snow depth assumption. Eleven of the catchments investigated here showed significantly different recession curve slopes between thick and shallow winter snow packs, but there was no clear pattern. Out of 11 catchments with significant differences in thick and shallow snow packs six catchments show the expected higher recession curve slope during thick snow depths.

Shallow snow depth (here, depths below 20 cm) periods and winter air temperatures were combined to identify years with higher than average (and lower than average) frozen soil depth. Research shows soils to freeze deeper when cold temperatures occur during periods with little snow (Hardy et al., 2001; Osterkamp, 2007). Ten catchments had significant differences, with nine catchments having higher recession curve slopes for shallow snow warm winters (Table 2). This result confirms our expectation that frozen ground decreases recession curve slopes. Using snow depth in combination with winter air temperatures to group years based on frozen soil depth yielded much clearer results than grouping based on snow depth only. Kohler, Brandt, Johansson, and Callaghan (2006) modelled snow depth in Abisko and concluded increasing snow depth averages over the last century. Åkerman and Johansson (2008) also found that five of their nine catchments close to Abisko also had increasing snow depths. In fact, for much of the Arctic, a thicker snow pack is becoming more common while winter temperatures are increasing (Lind & Kjellström, 2008). Our results suggest that this direction of climate change likely causes more non-linear storage discharge relationship throughout the arctic.

We provide evidence that recession curve slopes depend on preceding winter conditions. These winter conditions control when flow paths start to flow and the amount of flow paths 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 curve slopes were not yet clearly increasing. The four pre-1990 catchments showed no significant difference for any analysis. If these pre-1990 analyses had been significant we could suggest that our soil frost related proxies directly control between year variability in recession curve slope. However, we did not find such direct controls on variability, but we did find clear long-term controls. Therefore, it becomes more likely that the observed changes in recession curves slopes are a result of the catchments slowly adapting to climatic changes during the last decades. The limited amount of data pre-1990 may also be an important reason for no significant difference during that period.

4.5 | Effects of frozen soil and permafrost on 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 was found 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. Based on our results, 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). Frampton et al. (2011) and Sjöberg et al. (2016) looked at either a numerical model for non-isothermal, three-phase flow of air and water or recession intercepts and annual minimum discharge determined by groundwater and permafrost. While Walvoord et al. (2012) carried out a numerical simulation of flow paths and their interaction with winter baseflow water budget. 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.

Seasonally frozen soils along with decreasing amounts of permafrost influence groundwater flow in Arctic catchments (Figure 6). Storage-discharge relationships in the catchments considered in this current study are becoming increasingly non-linear, though the degree of change likely depends on the specific catchment's topography, differences in bedrock and surficial geology and current continuity of permafrost presence. We hypothesized that recession curve slopes are partly controlled by frozen ground and in turn react to thawing

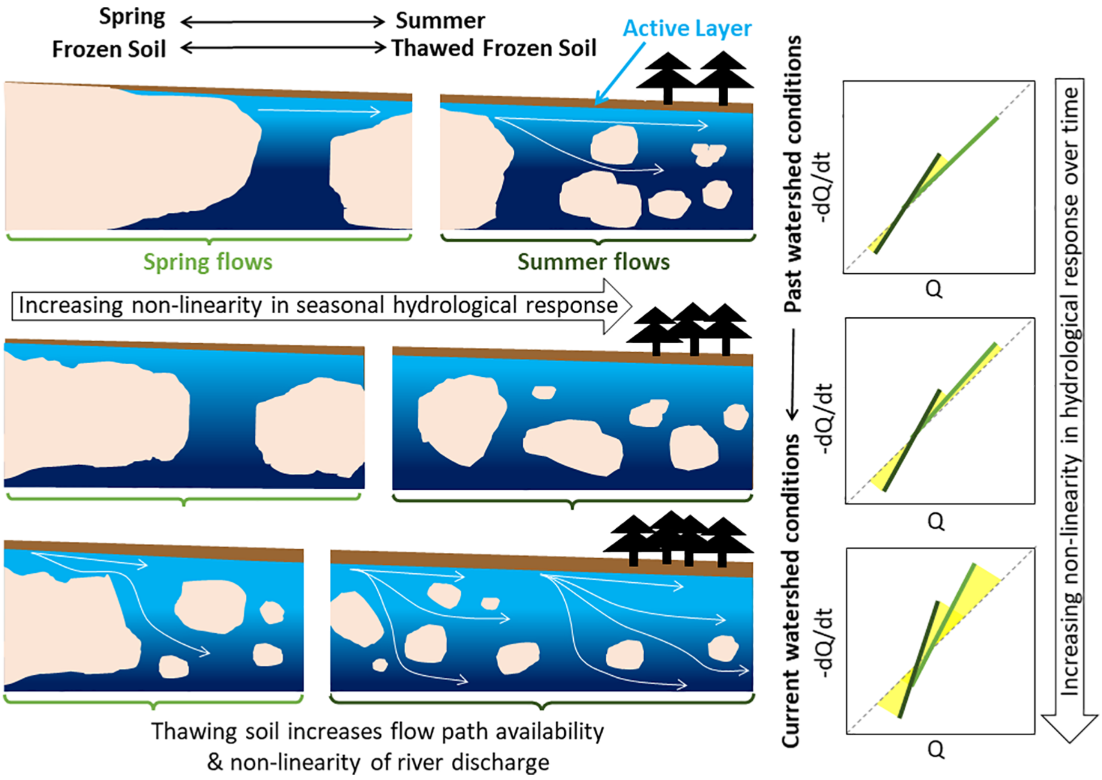

FIGURE 6 A diagram showing how the change in seasonally frozen soil can potentially affect the flow paths/conductivity of the soil and influence the recession curve. The light green represents spring and shows spring recession while the dark green represents summer. The active layer (light blue) increases as the frozen soils thaw in spring. An accumulation of the organic layer (brown) includes an increasing amount of ecology. The white arrows are representative of the increasing number of flow paths

ground. Our results support this hypothesis, but we cannot exclude that other changes within the catchments could have similar effects on recessions. This study did not examine, for example, the potential effect of soil moisture on the recession curve slope. Other studies are suggesting Arctic catchments are becoming wetter, which may also change the storage-discharge relationship, and consecutively, the recession curve slope (Raynolds & Walker, 2016; Rowland et al., 2010). Changes in the recession curve slope could also be caused by land cover change. As vegetation migrates further north into the Arctic, new flora and soil biota will have different water requirements and effects on soil structure, which influence water flowing to the rivers (Costa, Botta, & Cardille, 2003).

While we set out to answer how permafrost and seasonally frozen soil thaw affect recession curve slopes, we must acknowledge that 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 at high elevation. Gruber and Haeberli (2009) state that for mountainous regions, permafrost is impacted by slope of a catchment, topography, elevation and strong winds dictating snow cover conditions. Follow up research would benefit from looking similar increases in the non-linearity of the storage discharge relationships in flatter permafrost regions where permafrost is still more continuous.

5 | CONCLUSION

We show that catchments in Northern Sweden have been undergoing a significant change in their discharge reaction to rainfall and snowmelt events since 1950 and especially since 1990. The storage-discharge relationships of thirteen out of sixteen investigated catchments has become more non-linear (i.e., mostly linear recessions (β = 0.8–1.3) in the period 1950–1970 increasing more non-linear recessions (β = 1.3–2.2) during the period 2010–2018) with a greater change in spring than summer. This means these catchments are better able to store their water under low to medium wetness conditions but release their water more quickly under wet conditions, making peak river discharge in the Arctic likely more unpredictable. In addition, we show that frozen soil depth, approximated by snow depth and air temperatures, affects storage-discharge relationships, with nine of the sixteen catchments exhibiting more non-linear relationships during years with shallow frozen soil depth. We hypothesized that these changes are primarily caused by disappearing permafrost and a reduced thickness of seasonal soil frost. Although 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. It is likely that 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 catchments 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 these trajectories into the future.

ACKNOWLEDGEMENTS

This work is part of the research programme Netherlands Polar Programme with project number ALWPP.2016.014, which is financed by the Dutch Research Council (NWO). We thank Claudia Brauer and an anonymous reviewer for their valuable comments which improved our manuscript.

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.

ORCID

Alexa M. Hinzman https://orcid.org/0000-0001-5364-4641
Ylva Sjöberg https://orcid.org/0000-0002-4292-5808
Steve W. Lyon https://orcid.org/0000-0002-1137-648X
Stefan W. Ploum https://orcid.org/0000-0003-1131-7153
Ype van der Velde https://orcid.org/0000-0002-2183-2573

REFERENCES

Akanegbu, J. O., Marttila, H., Ronkanen, A.-K., & Kløve, B. (2017). A current precipitation index-based model for continuous daily runoff simulation in seasonally snow covered sub-arctic catchments. *Journal of Hydrology*, *545*, 182–196. https://doi.org/10.1016/j.jhydrol.2016.12.020

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/10.1002/ppp.626

Anderberg, S. (1991). Historical Land Use Changes: Sweden. F. M. Brouwer A. J. Thomas & M. J. Chadwick *Land Use Changes in Europe: Processes of Change, Environmental Transformations and Future Patterns*, (403–426). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-011-3290-9_18.

Bense, V. F., Ferguson, G., & Kooi, H. (2009). Evolution of shallow groundwater flow systems in areas of degrading permafrost. *Geophysical Research Letters*, *36*(22), 401, https://doi.org/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/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.*, *121*, 621–649. https://doi.org/10.1002/2015JG003131

Brown, J., Ferrians, O. J., Heginbottom, J. A., Melnikov, E. S., & Akerman, J. (1997). *Circum-Arctic map of permafrost and ground-ice conditions*, Circum-Pacific Map Series CP-45, Washington, DC: U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. https://doi.org/10.13140/RG.2.1.2994.9040.

Brutsaert, W. (2008). Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. *Water Resources Research*, *44*(2), 409. 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)*, *117*(22), 110. 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. (2003). Multiple Regression/Correlation with Two or More Independent Variables. *Applied multiple regression/correlation for the behavioral sciences*, 3rd (64–99). Mahwah, NJ : . Lawrence Erlbaum Associates Publishers.

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

Gisnås, K., Etzelmüller, 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, F. S., III, 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). Boca Raton, Fl: Lewis Publishers.

Hinzman, L. D., Yoshikawa, K., & Kane, D. L. (2005). Permafrost controls on hydrological processes in a changing climate. In *World Water Congress 2005: Impacts of Global Climate Change—Proceedings of the 2005 World Water and Environmental Resources Congress*, Red Hook, NY: Curran Associates, Inc. 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

Jachens, E. R., Rupp, D. E., Roques, C., & Selker, J. S. (2020). Recession analysis revisited: Impacts of climate on parameter estimation. *Hydrology and Earth System Sciences*, *24*(3), 1159–1170. https://doi.org/10.5194/hess-24-1159-2020

Jorgenson, M. T., Romanovsky, V. E., Harden, J. W., Shur, Y. L., O'Donnell, J. A., Schuur, E. A. G., … Marchenko, S. (2010). Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest Research*, *40*(7), 1219–1236. https://doi.org/10.1139/X10-060

Karlsen, R. H., Bishop, K., Grabs, T., Ottosson-Löfvenius, 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), 429. 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*, *25*, 91–113. 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

Lagerbäck, 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., & Sponseller, A. (2018). How landscape organization and scale shape catchment hydrology and biogeochemistry: Insights from a long-term catchment study. *Wiley Interdisciplinary Reviews: Water*, *5*(2), E1265. 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*, *34*, 969–981. 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

Lind, P., & Kjellström, E. (2008). *Temperature and precipitation changes in Sweden: A wide range of model-based projections for the 21st century*. Report Meteorology and Climatology 113, Norrköping, Sweden: SMHI.https://www.smhi.se/en/publications/temperature-and-precipitation-changes-in-sweden-a-wide-range-of-model-based-projections-for-the-21st-century-1.6647.

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), 1499–1503. 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., Mörth, M., Seibert, J., … Troch, P. A. (2009). Estimation of permafrost thawing rates in a subarctic 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., Jarsjö, 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/10.1002/hyp.10304

Marks, D., Winstral, A., Reba, M., Pomeroy, J., & Kumar, M. (2013). An evaluation of methods for determining during-storm precipitation phase and the rain/snow transition elevation at the surface in a mountain basin. *Advances in Water Resources*, *55*, 98–110. https://doi.org/10.1016/j.advwatres.2012.11.012

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), 519. https://doi.org/10.1029/2011WR011552

Peel, M. C., & Blöschl, 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., Mård, 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), 5004. 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

SHMI. (2018). The Swedish Agency for Marine and Water Management—Data. Retrieved February 23, 2018, from https://www.smhi.se/data.

Silfverstrand, N. (2019). Land use and land use change-Implications on biogenic carbon balance.

Sjöberg, 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/10.1002/2015WR017571

Sjöberg, 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), 401. 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.*, *53*, 2598–2604. 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/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., & International Permafrost Association. (1998). *Multi-language glossary of permafrost and related ground-ice terms in Chinese, English, French, German, Icelandic, Italian, Norwegian, Polish, Romanian, Russian, Spanish, and Swedish*, Calgary, Alberta: International Permafrost Association, Terminology Working Group, 1998.

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), 524. 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., Mård, 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

Zhang T., 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. http://dx.doi.org/10.1080/10889379909377670.

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, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, *43*(4), 002. https://doi.org/10.1029/2004RG000157

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Hinzman AM, Sjöberg Y, Lyon SW, Ploum SW, van der Velde Y. Increasing non-linearity of the storage-discharge relationship in sub-Arctic catchments. *Hydrological Processes*. 2020;34:3894–3909. https://doi.org/10.1002/hyp.13860