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Overview: Cascading spatial, seasonal, and temporal effects of permafrost thaw on streamflow in changing nested Arctic catchments

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Abstract:

In the Arctic, the thawing of permafrost affects how catchments store and release water. However, the effects of thawing on the hydrological response remain poorly documented. In addition, it remains unclear how the effects of a thawing landscape will propagate through nested catchments. Here we investigate 10 nested catchments within the Yukon basin (Alaska and Canada) to study how permafrost thaw impacts catchments' streamflow seasonality and storage-discharge relationships, and how these effects cascade through the nested catchments, from headwaters to downstream. Our results indicate that upstream catchments, characterized by continuous permafrost, have stronger streamflow seasonality and that these catchments also exhibit the most nonlinear storage-discharge relationships. Larger catchments downstream sustain year-round streamflow with baseflow continuing during winter. Since the 1950s flow regimes have become increasingly seasonal in the upstream catchments, with an earlier and more abrupt freshet, whereas further downstream flow seasonality has remained stable. Across the Yukon, storage-discharge relationships for 9 out of 10 sub-catchments have become increasingly nonlinear over time, with the biggest change occurring in the largest downstream catchments. In smaller catchments, each season has distinct recession characteristics, but those seasonal differences are not apparent further downstream. Upstream catchments are strongly influenced by localized change, whereas downstream catchments receive the effects of many different localized upstream impacts, making it difficult to detect a singular cause of change. Seasonal and long-term shifts in storage-discharge relationships are typically not accounted for by hydrological models and make accurate streamflow predictions more difficult. These shifts highlight how the changing landscape of the Arctic has far-reaching hydrological consequences.

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1 Introduction

The Arctic is warming at a faster rate than any other region in the world (Rantanen et al., 2022). The Arctic is heterogeneous, as polar and subpolar zones feature many biomes, various habitats, and diverse soil compositions. The arctic desert, tundra, taiga, and boreal forest zones are all connected by the hydrologic continuum, by water moving from soil to headwater streams in uplands, through lowlands, and eventually to high-order streams in coastal areas. (McKenzie et al., 2021a).

Permafrost is a ubiquitous feature of the Arctic. Not considering the impact of permafrost on Arctic rivers will give an incomplete understanding of how Arctic catchments behave, especially now that the permafrost is thawing. Changes in catchment hydrology caused by permafrost thaw can lead to changes in groundwater flow, biodiversity, and the development of lakes and unfrozen conduits for groundwater (taliks) (Tananaev and Lotsari, 2022). Thawing catchments in the Arctic have undergone changes such as lowering of the permafrost table, marked subsidence of the ground surface, increased active layer thickness, and the expansion and connection of previously isolated taliks (Jin et al., 2022). In addition, in the Arctic, where direct human-ecosystem interactions are limited, land-cover change determined by climate change and permafrost thaw influences streamflow more than human-induced landcover change (Frey and McClelland, 2009).

Arctic hydrologic responses to climate warming vary between seasons (Wang et al., 2021). Firstly, the thawing permafrost can increase the hydrologic connectivity between aquifers and surface waters (Lamontagne-Hallé et al., 2018; Chiasson-Poirier et al., 2020). This can lead to increased surface-subsurface water exchange. Secondly, a thicker active layer can contribute to the melting of excess ground ice but also allows soils to store more water. This can increase streamflow in winter due to the development of the supra-permafrost aquifers allowing for groundwater flow below the seasonal frost layer (Lyon and Destouni, 2010; Wellman et al., 2013; Walvoord and Striegl, 2007a; Walvoord et al., 2019). Finally, a longer thaw season can contribute to the thickening of the active layer, which in turn delays the active layer freeze-up

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and will also contribute to increased winter river runoff (Sjöberg et al., 2021). Also, the percentage of permafrost coverage will cause different hydrologic responses. For example, in catchments with higher permafrost presence, more water leaves the catchment as discharge while in catchments with less permafrost coverage, there is water loss in the form of evapotranspiration and infiltration into deeper groundwater flow paths (Koch et al., 2022). These impacts are heavily intertwined and therefore make it hard to isolate singular changes. (Asano et al., 2020; Karlsen et al., 2016; Lyon et al., 2012)

The impacts of permafrost thaw on catchment hydrology are widely variable throughout the Arctic and the temporal rate of permafrost degradation also differs substantially between locations (Obu et al., 2019; Sergeant et al., 2021). If the climate warms, 0.1˚C in 10 years, a trend seen in (Bekryaev et al., 2010) which does not include the current polar amplification occurring, catchments with mean annual air temperature around 0˚C will be affected more than catchments with a mean annual air temperature of -5˚C. Effectively, those catchments situated on that temperature threshold will be unable to re-freeze previously thawed permafrost in winter, exacerbating the thawing rates of permafrost while catchments with lower mean annual air temperatures have thicker active layers in summer but refreeze completely in winter (Åkerman and Johansson, 2008; Cooper et al., 2022).

Recession analysis uses streamflow records to provide insight into groundwater movement at the catchment scale. Traditionally, recession analysis quantifies baseflow dynamics, and the catchment water balance by inferencing the unconfined aquifer storage and release relationship and has successfully represented the lateral redistribution of groundwater in land surface systems (Troch et al., 2013). Relating the changes in subsurface groundwater flow to changes in surface discharge has been a method of investigating the catchment's storage-discharge relationship to the change in climate. In permafrost-laden catchments, recession analysis has been used in a round-about way to evaluate the health of the permafrost (e.g., if there is an increase in active layer thickness, the amount of groundwater that can be stored in a catchment changes which can influence flow paths in a catchment and therefore be detected in

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the recession analysis). It can illustrate permafrost thaw trends by making similar inferences to the catchment's storage dynamics, such as the active layer thickening and the changing groundwater flow (Hinzman et al., 2020, 2022).

Previous studies (Lyon et al., 2009; Brutsaert and Hiyama, 2012) have tested if an increased active layer thickness will lead to an increase in the recession curve slope. Recent work by Sergeant et al. (2021) echoed knowledge of the complexity of Arctic systems and found a dominant decrease in the recession curve intercept (i.e., the rate of discharge decline at a discharge of 1mm/d during a recession, indicating an increase in baseflow) after examining over 300 Arctic catchments from 1970 to 2000. Camporese et al. (2014), Cooper et al. (2022), and Sergeant et al. (2021) used the nonlinear relationships between saturated soil thickness and average baseflow to infer changes in the active layer thickness and found that the growth rate of the active layer has been accelerating in the last 20 years. Clearly, there are many ways how surface and subsurface processes affect each other. For that reason, the relationship between streamflow and storage does not yet have a concise explanation. In addition, due to the heterogeneous nature of the Arctic, dissimilar results should be expected.

While there has been ample research showing a change in the recession curve slope as permafrost degrades (Sjöberg et al., 2013; Bogaart et al., 2016; Hinzman et al., 2022), the question remains if changes in catchment streamflow are observable at all spatial scales or if the observed change diminishes at larger spatial scales. This is a crucial question because most streamflow of the larger rivers in the Arctic is measured with goals to estimate water and solute loads to the Arctic Ocean, but these large river systems are potentially less informative as indicators of permafrost change.

Here we study the effects of permafrost thaw on spatial differences, seasonal changes, and long-term shifts of streamflow seasonality and storage-discharge relationships in the Arctic. We focus on how these changes vary across nested catchments with spatial scale and how any effects of thawing may propagate downstream. This helps to understand how the effects of permafrost thaw on streamflow vary across spatial scales.

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2 Methods

2.1 The Yukon Basin

We used data from 10 nested catchments from the Yukon basin in Alaska and Canada. These catchments have a wide range of sizes as they cover the relatively smaller upstream catchments, up to almost the entire basin near the mouth of the river (Figure 1; Table 1).

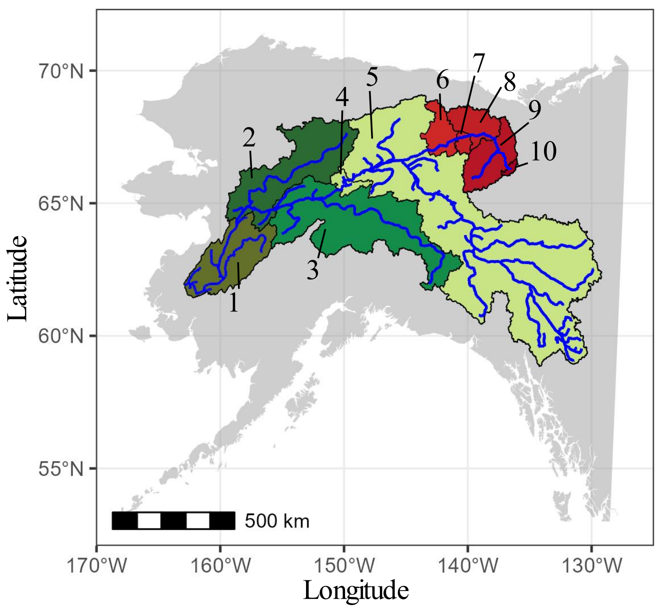

Figure 1. Outline of catchments, the blue lines indicate the river network, the smallest catchments are red and the rivers flow into the next larger catchment which changes to green. The catchments are numbered and correspond to Table 1.

We downloaded daily discharge data from the Global Runoff Data Centre (GRDC). Monitoring for three catchments started in the 1950s, three in the 1960s, and three in the 1970s with the latest catchment record starting in the 1980s. Four catchments have their data record continue into the 21st century. Pilot Station has the longest dataset with 46 years, followed by Steven Village with a dataset of 45 years. The exact date range and length of the record can be found in Table 1.

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Meteorological data, such as precipitation and potential evapotranspiration, were obtained from the Global Historical Climatology Network Daily (GHCN - Daily) dataset hosted by the National Centers of Environmental Information (NCEI). In cases of missing data, we used precipitation and potential evapotranspiration data from the gridded ERA5 dataset (Muñoz Sabater, 2019, 2021).

Table 1. Information on 10 catchments used in this study.

Catchment Name (#)	River	Period	Lat (˚)	Long (˚)	Area (km^2)	Missing Data
Pilot Station (1)	Yukon	1975-2020 (46)	61.9337	-162.8829	831390	18.4%
Kaltag (2)	Yukon	1956-1966 (11)	64.3271	-158.7219	766640	0.0%
Ruby (3)	Yukon	1956-1978 (23)	64.7405	-155.4919	670810	4.8%
Rampart (4)	Yukon	1956-1967 (12)	65.5065	-150.1734	516446	17.2%
Stevens Village (5)	Yukon	1976-2020 (45)	65.8751	-149.7203	508417	11.5%
Fort Yukon (6)	Porcupine	1964-1979 (16)	66.9903	-143.1404	76405	33.7%
International Boundary (7)	Porcupine	1987-2019 (33)	67.4239	-140.8938	59829	15.6%
Old Crow (8)	Porcupine	1961-1995 (35)	67.5639	-139.8833	55400	31.3%
Bell River (9)	Porcupine	1964-1995 (32)	67.4403	-137.7836	36000	44.5%
Dempster Highway Bridge (10)	Eagle	1978-2017 (40)	66.4417	-136.7083	1720	60.6%

We determined topography and permafrost presence by using the Circum-Arctic Map of Permafrost and Ground-Ice Conditions dataset (Brown et al., 2002) from the National Snow and Ice Data Center (NSIDC). The largest catchments are flatter, with alpine conditions from the south consisting of the Alaska Range, and the Kuskokwim Mountains with moderate Arctic conditions. The smaller catchments are further North, in a mix of alpine regions (Brooks Range and Ogilvie Mountains) and lowland regions and moreover colder climate conditions (Figure 2a). Lowlands are defined by (Brown et al., 2002) as intra- and intermontane depressions and terrains characterized by thick overburden cover (5-10m). While the uplands included mountains, highlands ridges, and plateaus characterized by a thick overburden cover (>5m) or exposed bedrock. We determined that during 2002, (when the Circum-Arctic map was first published), the smaller, more Northern catchments were in a continuous permafrost region while the downstream catchments had greater sections that encompass discontinuous and sporadic permafrost regions (Figure 2b).

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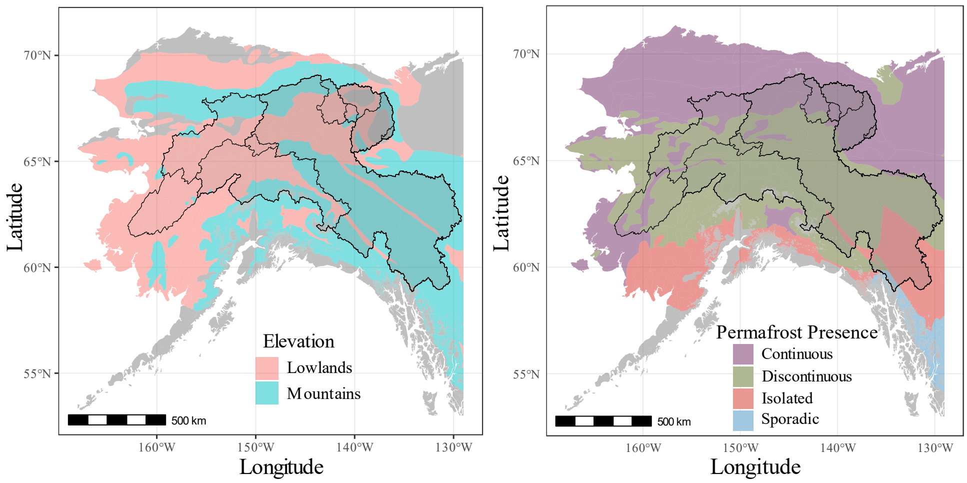

Figure 2. Outline of catchments with topography (a) and side-by-side of permafrost presence (b).

2.2 Streamflow and recession analysis

Discharge data were originally collected in cubic meters per second. We convert these data into specific discharge (i.e., mm/d) to allow more direct comparison between the catchments of strongly varying sizes. In addition, we calculate ratios of average monthly discharge to the average annual discharge (i.e., Pardé coefficients), first utilized by Maurice Pardé in 1933 and still used by hydrologists today to allow direct comparison of the streamflow seasonality between catchments (Curran and Biles, 2021; Poschlod et al., 2020).

Many studies have expanded on Brutsaert and Nieber's (1977) work on recession analysis and Kirchner's (2009) work on Arctic catchments to further the understanding of permafrost's control of the catchment's response (Karlsen et al., 2019; Ploum et al., 2019; Sergeant et al., 2021). The basic recession curve analysis used in this study follows the method first explained in Hinzman et al. (2020) and then expounded in Hinzman et al. (2022) A concise explanation is that while the hydrograph is reclining (Figure 3a), signifying no extra influence from meteorological factors, the rate of change in discharge (dQ, [mm/d/d]) over a change in time (dt, [d]) can be equated to the discharge (Q, [mm/d]) and the sensitivity of discharge to change in groundwater storage (dQ/dS, [d^{-1}]), which in turn is approximately a power function of the

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discharge (Q) (Eq.1). The resulting constants (Figure 3b), α and β can be interpreted as the intercept (α, [mm$^{1-\beta}$d$^{\beta-2}$]) and the slope (β, [-]) of the recession curve, as explained in (Kirchner, 2009).

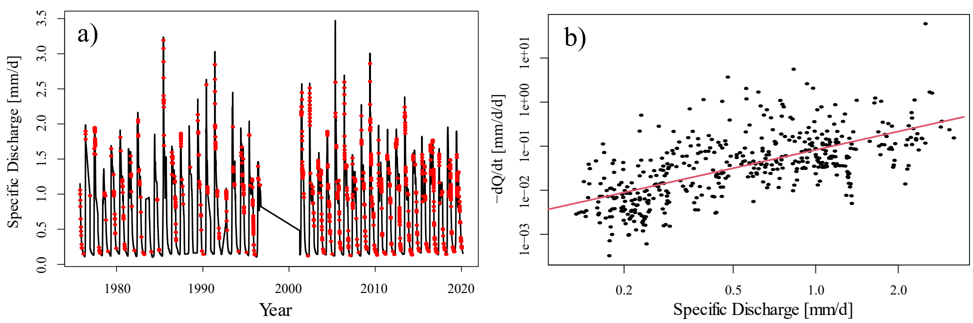

Figure 3. Hydrograph (a) and recession curve (b) of Pilot Station, red dots in (a) indicate recession points, which are then used in Figure 1b. The red line in (b) is the recession curve slope (β), which is obtained by a linear regression. The hydrograph (a) has a y-axis of the specific discharge. Specific discharge is discharge divided by catchment area. The specific discharge is seen in the x-axis of (b), and the y-axis is the change of specific discharge over the change of time.

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

2.3 Temporal change analysis

Our paper focuses on changes in the catchments' streamflow dynamics, as seen in changes in the specific discharge or changes in the slope of the recession curve, to be referred to in the future as β. Previous studies on arctic recessions (Lyon et al., 2009; Sjöberg et al., 2013; Evans et al., 2020; Lyon and Destouni, 2010), held β constant (β = 1) and focused on the recession intercept (α). Our focus on β is to characterize the amount of water moving through the catchment and to better examine the non-linear or linear relationship between discharge and groundwater storage. The length of the data collected is substantial for five catchments. They are Pilot Station (46 years), Ruby (23 years), Stevens Village (45 years), International Boundary (33 years), and Bell River (32 years), (Table 1). These catchments were gauged during different time periods, thus, for comparison the datasets were divided into halves (early and later years). This allows for comparison of hydrological changes within the catchments themselves as well as

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direct comparison of the catchments that do have overlapping time series. We characterize streamflow seasonality (as expressed by Pardé coefficients) and streamflow recession behavior (as expressed by β) for both the earlier and later periods. There are significant gaps in data collection for the Bell River and Dempster Highway Bridge. Those gaps arise from no stream discharge monitoring rather than a technical malfunction in data collection equipment. Other data gaps come from reduced monitoring frequency, especially in the earlier times of data collection as well as natural events like extreme weather conditions or floods that disrupt the normal functioning of measurement stations.

3 Results and discussion

3.1 Spatial patterns in seasonality and streamflow recessions

All catchments of the Yukon Basin have strongly seasonal streamflow regimes, but the degree of seasonality varies and is mediated by the catchment location within the Yukon River basin (Figure 4). Average monthly discharges for all catchments, as expressed by Pardé coefficients, indicate that smaller catchments that are located further upstream have relatively higher spring streamflows than the more downstream catchments. The smallest catchment, Dempster Highway Bridge (area = 1720 km^2) has its highest mean monthly flow around May. This freshet is almost five times larger than the mean flow of this catchment. During July and August, flow rates show a slight increase caused by typically higher precipitation rates during summer than other periods of the year. From November through March flow rates become near-zero. The largest catchment (Pilot Station, area = 831,390 km^2) has a more dampened highest mean monthly flow that also occurs later in the season. This peak flow is ~ 2.5 times the catchment's mean monthly flow rate and occurs around June. From thereon, flow reduces over summer, and low flows (Pardé coefficient ~0.25) persist also during the winter period up to the freshet. The other nested catchments have maximum seasonality patterns that fall between these two upstream and downstream end-member catchments. Overall, the Pardé coefficient indicates that larger catchments are less impacted by local factors throughout the year, resulting in more

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consistent year-round streamflow. Curran and Biles (2021) analyzed Pardé coefficients for 253 Alaskan catchments grouped by subclasses like winter temperature and basin elevation. The catchments they classified as driven by snowmelt or rainfall streamflow were comparable to the catchments in our study. Furthermore, their Pardé coefficients were similar, and their conclusion of shifting geographic seasonality echoed our own findings.

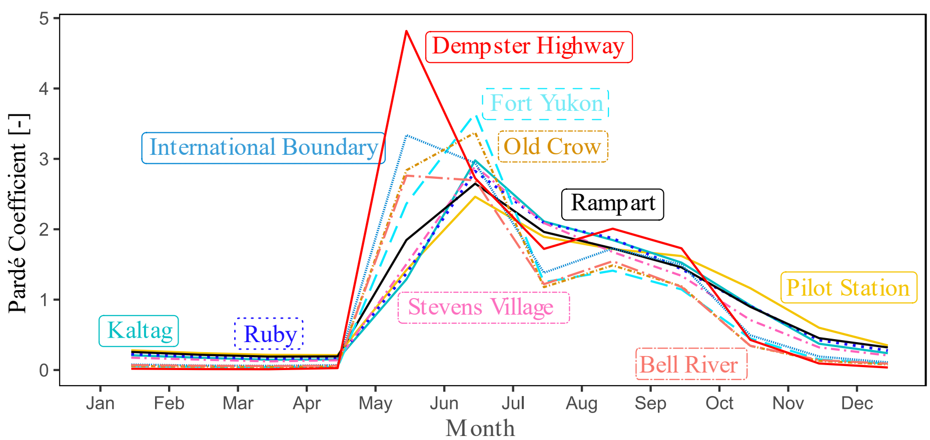

Figure 4. Seasonal flow regimes of the nested catchments within the Yukon basin. Comparison of Pardé coefficients, the catchments located in the North tend to have higher monthly Pardé coefficients compared to the catchments in the South, except during the winter months, when the northern catchments do not have any streamflow.

Streamflow recession behavior for all seasons over the whole times series, as characterized by the dimensionless recession slope β, is also mediated by the catchment's location within a basin (Figure 5). Smaller upstream catchments (<100,000 km^2) tend to have steeper recession curve slopes than the larger downstream catchments (Figure 5). Spatially, the smaller catchments have a higher percentage of continuous permafrost (Figure 5) as well as steeper slopes. Interestingly, steeper slopes correlate with greater changes in β was a result found in (Hinzman et al., 2022), which may explain the findings here. The catchments' permafrost becomes mostly discontinuous downstream of Stevens Village (area = 508,417 km^2). In larger catchments (> 500,000 km^2) further downstream than Stevens Village, β decreases suddenly and there is a wider range of recession curve slopes (0.80-1.70), while upstream β appears relatively constant and high (~1.5-1.7), with the exception of Fort Yukon (β = ~1.0). This wide range of

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recession curve slopes seen in the large catchments can be attributed to those catchments having different time periods of data collection.

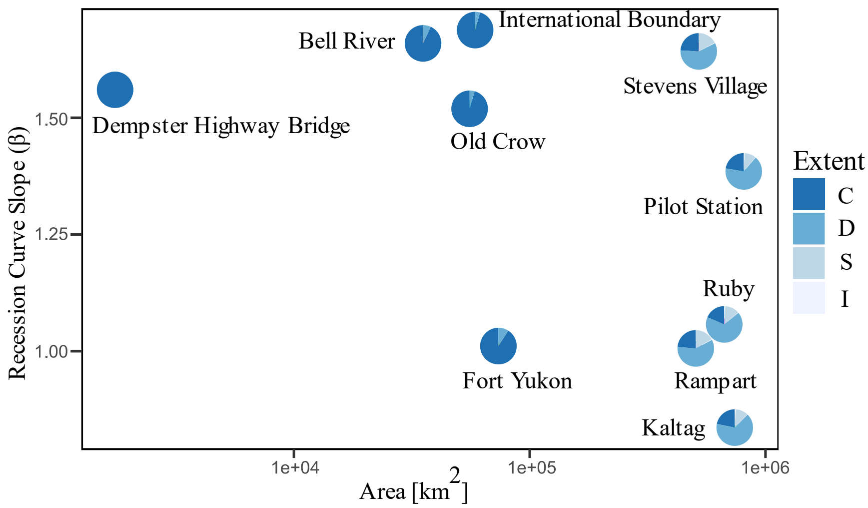

Figure 5. Recession curve slopes vs area of catchments. Note that the period for which the recession curve slopes are determined may vary between stations (Table 1). The pie graphs indicate the percentage of different permafrost for each catchment during the early 2000s. C is continuous permafrost (90-100%), D is discontinuous permafrost (50-90%), S is sporadic permafrost (10-50%) and I is isolated permafrost (0-10%).

3.2 Seasonal shifts in recession behavior

The rate at which frozen ground thaws varies throughout the year, and the effects of that thawing (i.e. differences in active layer thickness, taliks that widen/open and narrow/close, and permafrost thawing from the bottom) can result in distinct recession curve slopes between seasons. Several studies have looked at seasonal effects of ground freeze-thaw processes on streamflow, (Ploum et al., 2019; Wang et al., 2020). We first illustrate these seasonal shifts by calculating recession curve slopes for spring, summer, and fall at Pilot Station and Bell River (Figure 6). While winter recession points were included in the graphs, the winter recession curve slope was not considered as many of the upstream catchments do not have winter recessions due to low or no streamflow (Figure 4). At Pilot Station (Figure 6a), the recession curve slope does not substantially vary throughout the seasons, except for spring. In spring, the β-value (~1.8) is higher than in the other seasons where β is ~1.0-1.2. For the upstream catchment of Bell River

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(Figure 6b), there are much stronger seasonal differences in recession curve slopes. Here, fall has the highest recession curve β (~2.2) whereas the slope is lowest during spring (~0.78). More generally, when we consider seasonal recession curve slopes across all catchments (Table 2), we find that downstream catchments tend to have lower fall recession curve slopes, whereas in upstream catchments the recession curve slope continues to increase from spring to fall. This shift from spring to fall, where the recession becomes more non-linear, indicates that as the seasons progress, streamflow responses become more sensitive to storage variations and thereby potentially harder to predict. This echoes our seasonal findings from an earlier paper focused on Swedish catchments (Hinzman et al., 2020) where the summer recession curve slope was greater than the spring recession curve slope but we also found that spring recession curve slopes were increasing at a more rapid rate the summer recession curve slopes.

These changes in seasonal behavior can be attributed to several factors. In the upstream catchments, the thawing active layer will allow for increasing subsurface flow, with spring having the shallowest thickness of the active layer and fall having the deepest thickness of the active layer, while in downstream catchments the thickness of the active layer can already be fluctuating within the areas of discontinuous permafrost, leading some areas to already have deep thickness of active layer as well as with streamflow of different seasons flowing from the upstream catchments creating a blend of spring, summer or fall discharge further obfuscating seasonal recessions. Increasing groundwater flow as found in studies from Lyon et al. (2010) and Walvoord and Striegl (2007) lead researchers to suggest that this increase leads to more non-linearity in streamflow response and the increased storage capacity lengthens timescales and leads to the increased blending of streamflow seasonalities (Wang et al., 2022; Curran and Biles, 2021).

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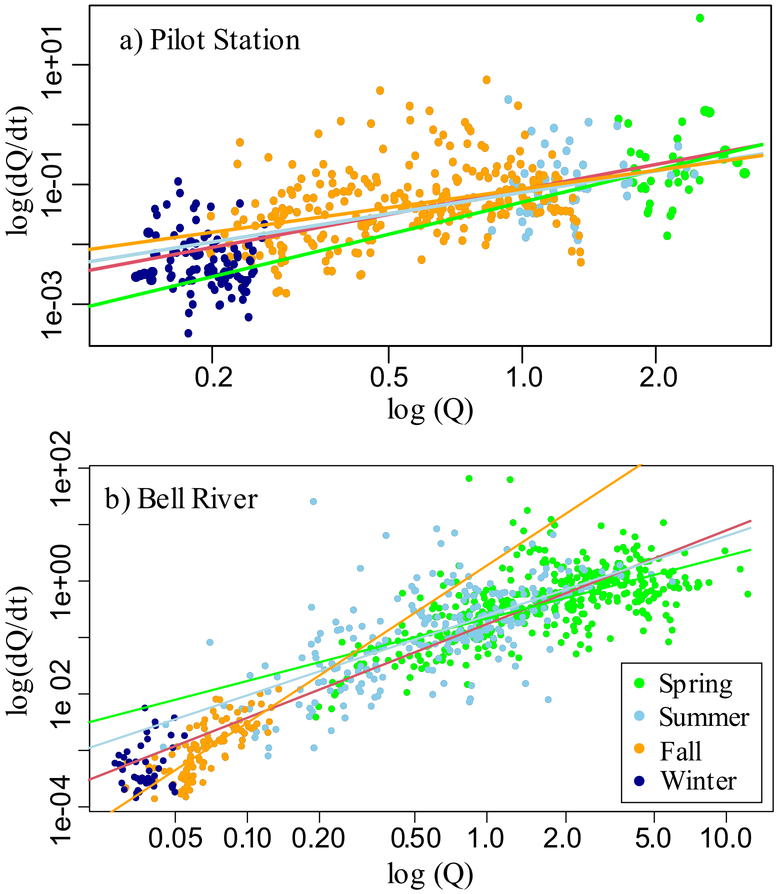

Figure 6. Pilot Station (a), and Below Bell River (b) recession curve with seasonal recession points. Red is the overall recession curve slope. Light green represents the recession curve slope and recession points that occurred in spring. Light blue represents the recession curve slope and recession points that occurred in summer. Orange represents the recession curve slope and recession points that occurred in fall. Dark blue represents recession points that occurred in winter. The y-axis is log of the change of discharge over the change in time, and the x-axis is the log of discharge.

Table 2. Recession Curve *β* results, stratified per season.

Catchment	Area (km^2)	Overall β	Spring β	Summer β	Fall β
Pilot Station	831,390	1.38	1.78	1.19	1.03
Kaltag	766,640	0.833	NA	1.06	0.701
Ruby	670,810	1.06	NA	3.04	0.872
Rampart	516,446	1.01	3.27	2.83	0.967
Stevens Village	508,417	1.65	1.25	NA	1.61
Fort Yukon	76,405	1.01	0.942	1.12	NA
International Boundary	59,829	1.69	1.2	1.25	1.82
Old Crow	55,400	1.53	0.902	1.27	2.44

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Bell River	36,000	1.66	0.779	1.38	2.17
Dempster Highway Bridge	1,720	1.56	0.46	1.42	1.54

3.3 Temporal change in seasonality and recession behavior

The changes in the Arctic are not confined solely to seasonal patterns; rather, the warming of the Arctic instigates enduring shifts in hydrological behavior over the long term. For catchments where we could divide the dataset into an early and late period (both with >7 years of (near-) continuous data), we calculate monthly Pardé coefficients for the early and the late period, using the average discharge value for the entire dataset, thus allowing for a comparison temporally and seasonally.

In most catchments, streamflow seasonality appears to be changing over time (Figure 7), whereby the patterns of change vary according to the location within the basin. In the upstream stations, the spring discharge peak has shifted towards an earlier start (Figure 7f-7j), and this freshet has not consistently changed its magnitude compared to the older period. In these upstream catchments, streamflow has remained marginal during early winter (October-December) and near zero throughout the later winter months (January-March). Similarly, for almost all of the downstream catchments (Stevens Village and larger), the freshet has slightly shifted towards an earlier start, while spring peak flows have remained similar, except in Rampart and Ruby. For Rampart the change in Pardé coefficients suggests greater streamflow throughout the second period while Ruby has less streamflow during the second period. Another shift we observe in downstream catchments are increases in streamflow throughout late fall and early winter (Oct-Dec), as indicated by the larger Pardé coefficients. While downstream catchments have year-round streamflow, later winter months streamflow has remained constant over the years, which is consistent with no changes seen in the winter months of upstream catchments (Fig. 7a-7j). Moreover, the earlier start of the season is clear in the upstream, smaller catchments and less pronounced in downstream catchments. However, for downstream catchments impacts extend into the late fall and early winter periods. Downstream catchments interact with larger and typically deeper groundwater aquifers. The flow through these aquifers

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has been shown to increase by permafrost thaw leading to larger baseflow and increasingly non-linear storage discharge relationships (Walvoord et al., 2012; Hinzman et al., 2020). Analyses of other basins, such as the Yana and Indigirka basins in Russia have shown shifting streamflows, with increasing streamflows into September, an increasing number of rivers not freezing in November or December, and earlier recorded freshet (Makarieva et al., 2019).

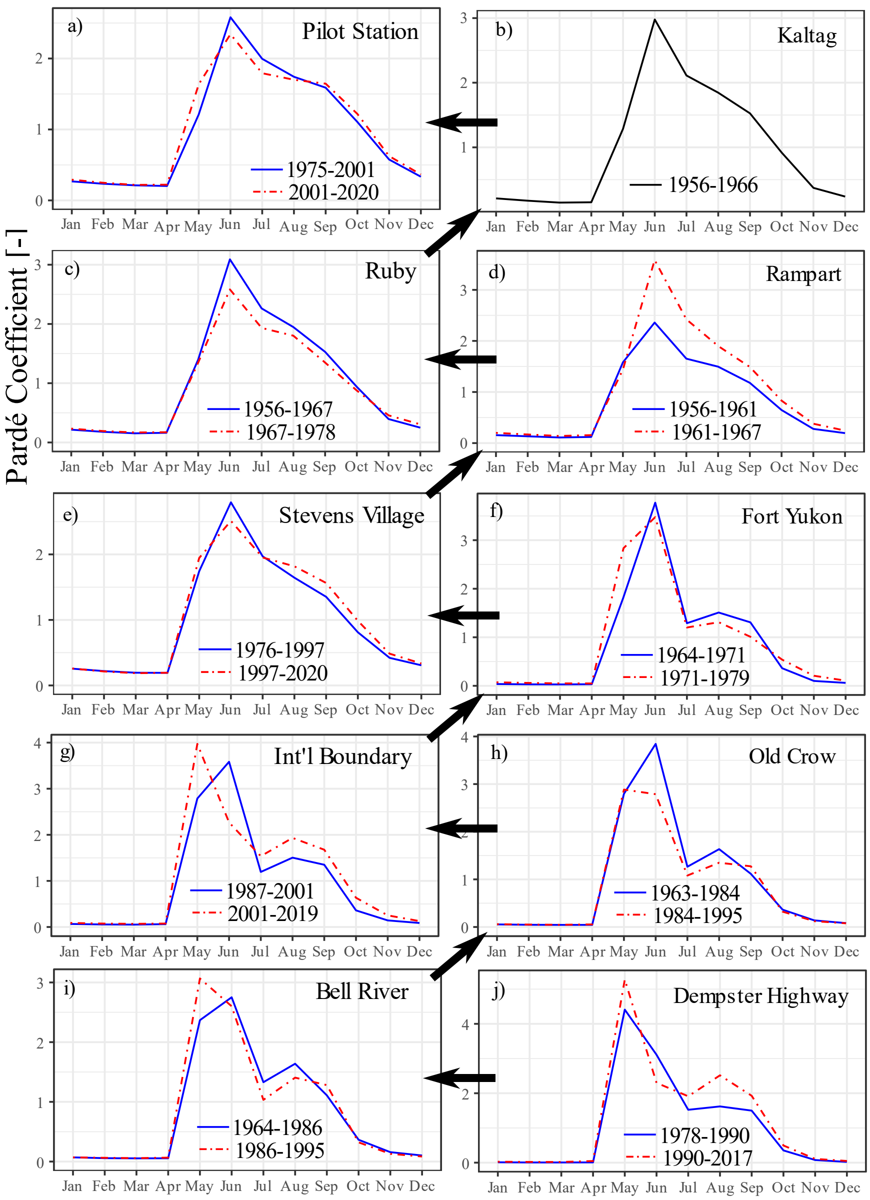

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Figure 7. Changes in the average monthly streamflow of catchments. Blue solid lines represent the earlier years of the dataset, and the red dotted line represents the later years of the catchment, the length of each catchment's record can be found in Table 1. The black arrows indicate the directions of the catchment flow.

Across the Yukon, 9 out of 10 sub-catchments' storage-discharge relationships have become increasingly nonlinear as time progressed. These changes are often substantial, as for example, Pilot Station shifts draining roughly linearly (early β = 0.93) towards substantially nonlinear (later β = 1.55). For most of the other catchments, β has increased roughly 0.3-0.4. The largest changes have occurred in the downstream catchments (most notably Pilot Station and Rampart), whereas changes in the upstream catchments (e.g., Old Crow, Bell River, Dempster Highway Bridge) tend to be of a smaller magnitude. Ruby and Rampart have large differences between early and later periods (early β = 0.706, later β = 1.06 and early β = 2.09, later β = 1.01, respectively), with the later β being almost identical to the overall β, which reflects there were few recession points captured in earlier periods compared to later periods. Few recession points in the earlier period may also cause larger uncertainty in the early β of Ruby and Rampart. Our results of increased non-linearity in β differed from the work by Sergeant et al. (2021), who found a decreasing recession curve β for a majority of their catchments. However, an explanation for this difference could be in the length of the dataset, with Sergeant using data from 1970-2000 and our study encompassed data from 1954-2020, an extra 40 years. Other studies agree with our findings of increased β values (e.g., McKenzie et al., 2021b; Ploum et al., 2019; Wang et al., 2022).

Table 3. Recession characteristics for early and later periods. 3.4 Nested catchments as expenditures of missing data

Catchment	Area (km^2)	Overall β	Period	Early β	Period	Later β
Pilot Station	831,390	1.38	1975-2001	0.93	2001-2020	1.55
Kaltag	766,640	0.833	1956-1961	NA	1961-1966	NA
Ruby	670,810	1.06	1956-1967	0.71	1967-1978	1.06
Rampart	516,446	1.01	1956-1961	2.09	1961-1967	1.01
Stevens Village	508,417	1.65	1976-1997	1.37	1997-2020	1.8
Fort Yukon	76,405	1.01	1964-1971	0.80	1971-1979	1.2
International Boundary	59,829	1.69	1987-2001	1.68	2001-2019	1.71
Old Crow	55,400	1.53	1963-1984	1.32	1984-1995	1.72
Bell River	36,000	1.66	1964-1986	1.49	1986-1995	1.77

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Dempster Highway Bridge	1,720	1.56	1978-1990	1.36	1990-2017	1.69

In cases of missing data, which is a common issue within the Yukon basin and the Arctic more broadly, our analysis of cascading spatial, seasonal, and temporal effects of permafrost thaw on streamflow may help to fill data gaps. There are clear patterns in upstream and downstream differences in seasonal flow patterns (Fig 4), recession characteristics (Fig. 5), and temporal shifts of these flow patterns and recession characteristics (Figs 7a-7j). This implies that in cases of missing data (either because a gauge is not operational or because there is no gauge at all), we can use the data of surrounding catchments to estimate flow seasonality, recession behavior, and temporal shifts of the ungauged catchment. The most representative donor catchments are not necessarily the closest in geographic location, but they are the ones that most closely resemble the catchment's location within the river network, and the associated permafrost conditions. Such information is readily available across the entire Yukon basin (or even the Arctic) and thereby allows for wide application.

Such estimates could not only provide estimates in space, but also provide estimates in time. For example, Pilot Station data collection started in 1975, in other words, it was an ungauged catchment before 1975 and therefore earlier streamflow and recession behavior are unknown. However, data from a nearby and representative station (Kaltag) goes back to 1956. It is very similar in size (a 7.8% area difference), in permafrost characteristics (22.4% and 21.8% of the catchments are covered in continuous permafrost, with 66.7% and 66.3% covered by discontinuous permafrost) and in the relative location within the catchment. Using the data from Kaltag to estimate catchment behavior during the earlier years of an ungauged Pilot Station would be beneficial in creating a longer time frame of which to document changes in the catchment.

Data from similar-sized catchments further supports the use of data from other catchments to create a more complete data record, because both Pardé coefficients and recession curve slope are comparable in similar sized catchments. For example, the Pardé coefficients and

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the recession curve slopes of Pilot Station and Ruby are comparable over the period where data of the two catchments overlap for (i.e., earlier β_{PS} = 0.932 and later β_{Ru} = 1.06). In addition, the earlier period seasonal flow regime of Pilot Station (1975-2001) (the blue line in Fig. 7a) is almost identical to the later period seasonal flow regime of Ruby (1967-1978) (red line in Figure 7c). Another example is International Boundary and Old Crow, which only differ by 7.5% in size. These catchments have near-identical recession behavior (when the overlapping time period is considered) with a recession slope for International Boundary (1987-2001) of β_{IB} =1.68, and the later part of Old Crow (1984-1995) of β_{OC} = 1.72. Such transfer of data likely becomes increasingly reliable when catchment properties and the considered period better overlap. A study by Betterle and Botter (2021) found that nested catchments had less streamflow correlation than non-nested catchments that were more similar in area and geomorphic conditions, while we do not find similar findings in our nested catchments, it does lead credence that the dataset of similar catchments, nested or otherwise, can be used to create a more complete picture when data is not available.

4 Conclusion

The thawing of permafrost affects how Arctic catchments store and release water, but the effects of thawing on hydrological response are poorly documented. These effects will vary according to the location in the catchment, but it also is unclear how the effects of a potentially thawing landscape will propagate through nested catchments. Here we investigated 10 nested catchments within the Yukon basin (Alaska and Canada) to study how permafrost thaw impacts catchments' streamflow seasonality and storage-discharge relationships, and how these effects cascade through nested catchments, from headwaters to downstream. Our results indicate that upstream catchments, characterized by continuous permafrost, mostly have stronger streamflow seasonality, and that these catchments also exhibit the most nonlinear storage-discharge relationships. Larger catchments downstream sustain year-round streamflow with baseflow continuing during winter. Since the 1950s flow regimes have become increasingly seasonal in the upstream catchments, with an earlier and more abrupt freshet, whereas further downstream

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flow seasonality has remained stable. Across the Yukon, 9 out of 10 sub-catchments' storage-discharge relationships have become increasingly nonlinear over time, with the biggest change in the largest downstream catchments. In smaller catchments, each season has distinct recession characteristics, but those seasonal differences are not apparent further downstream. Upstream catchments are strongly influenced by localized change, whereas downstream catchments receive many different localized upstream impacts, making it difficult to detect a singular cause of the change. Seasonal and long-term shifts in storage-discharge nonlinearity are typically not accounted for by hydrological models and make accurate streamflow predictions with a changing climate and thawing permafrost more difficult. These shifts highlight how the changing landscape of the Arctic has far-reaching hydrological consequences.

Data availability:

The paper uses streamflow data obtained from the Global Runoff Data Centre (GRDC) The full dataset and documentation can be downloaded from: https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Home

The paper uses meteorological data obtained from the Global Historical Climatology Network Daily (GHCN - Daily) https://www.ncdc.noaa.gov/cdo-web/ The full dataset and documentation can be downloaded from DOI:10.7289/V5D21VHZ

For missing meteorological data the paper used gridded ERA5 dataset. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview The full dataset and documentation can be downloaded from: DOI: 10.24381/cds.adbb2d47

The paper used data from Circum-Arctic Map of Permafrost and Ground-Ice Conditions https://nsidc.org/data/ggd318/versions/2 The shapefiles and documentation can be downloaded here: DOI: 10.7265/skbg-kf16

For River Shapes the paper used Global River Classification (GloRiC) https://www.hydrosheds.org/products/gloric The shapefiles and documentation can be downloaded here: DOI: 10.1088/1748-9326/aad8e9

Author contribution:

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Declaration of interests:

At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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