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Hydrology and Earth System Sciences
Discussions

Trends in hydroclimate extremes: How changes in winter conditions affect seasonal baseflow and storage

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Abstract. Northern ecosystems experience rapid climatic change at a rate where average temperatures are increasing above global averages. Yet, for the boreal snow-dominated catchments that rely on the winter snow accumulation and spring melt for sustained stream flow across preceding seasons, much remains unknown about how catchment water storage and baseflow are affected. Here we used 40 years of data from the boreal Krycklan catchment, placed into a 130 climate record from a nearby location, to test how 27 extreme climate change indices have been affected, and how these, in turn, can explain seasonal low flows during the winter and summer. Our results show that while annual temperatures have increased by 2.2 °C over the last four decades, even more distinct seasonal impacts were detected, exemplified by eight extreme indices demonstrating that winters have become warmer with less precipitation. The analysis also showed that summers have become warmer based on four significant changes in climate indices. Using the significant winter indices to predict winter baseflow and winter/summer indices to predict summer baseflow we found that the accumulated degree day below zero (AFDD<0) was the best predictor of winter minimum flow and AFDD<0 and Summer maximum temperature (MaxTmax) were the best predictor of summer minimum flow. Additional isotopic analysis of stream flow partitioning found an increasing contribution of winter rain/snow in stream runoff during winter over the last 22 years, as well as a decreased contribution to the preceding summer stream flow. These findings imply that warmer winters have affected water storage and runoff patterns in the boreal catchment which can have important feedback on terrestrial ecosystems, particularly on water availability in later parts of the growing season.

1 Introduction

Over the past decades, high-latitude areas have undergone a warming trend exceeding the global average, with the region continuing to warm at a rate more than twice as fast as the rest of the world (Rantanen et al., 2022; Druckenmiller et al., 2021). The boreal zone is particularly sensitive to the changes in climate (Ali et al., 2024; Fu et al., 2023; Seidl et al., 2020) as its thermal regime strongly is affected by snow cover. Hence, temperature changes are likely to affect snow accumulation and the timing of melt (Bouchard et al., 2024; Friesen et al., 2021; Kim et al., 2012; Peng et al., 2013), which are mechanisms regulating the length of the growing season and phenology (Easterling, 2002; Way, 2011; Cleland et al., 2007). Consequently, shifts in the timing of the onset and end of winter are among the most fundamental impacts of climate change, which can increase the risk of severe, and in some cases irreversible ecological impacts. Yet, how changes in seasonal cycles, temperature and moisture regimes feedback on terrestrial ecosystems, biogeochemical cycles and hydrological cycles remain largely unknown.

Winter conditions define the timing and magnitude of hydrological processes within northern catchments particularly as seen in river runoff (Barnett et al., 2005; Blöschl et al., 2017; Hrycik et al., 2024; Murray et al., 2023). For instance, temperatures below freezing are conducive for precipitation to accumulate as snow and ice, which is made available for groundwater recharge during melting. The freezing period therefore determines the amount of water stored in catchments based on temperature departure below zero but also on the duration of the below-zero period and the subsequent melting rate (Stieglitz et al., 2001; Simons, 1967; Nygren et al., 2020). Any changes to the period of below freezing will ultimately affect the duration of the cold period with consequences for the water cycle leading to alterations in the flow regime (Blöschl et al., 2017). Already, current changes in the winter period indicate a significant trend in shorter ice duration, later freezing and earlier break-up dates from 1913–2014 in Sweden and Finland (Arheimer and Lindström, 2015; Hallerbäck et al., 2022). Such results have consequential effects on soil freeze/thaw cycles, and lake and river ice dynamics (Kim et al., 2012; Peng et al., 2013) across the northern hemisphere. Despite a growing body of literature, the implications of rapidly changing winters on groundwater recharge conditions, and how this will affect proceeding seasonal runoff dynamics, are still elusive.

Changes in river runoff are essential factors for assessing the effects of climate change on the hydrological cycle as the discharge is highly dependent on precipitation (P), evapotranspiration (ET), and changes in water storage across the entire watershed area (White et al., 2007). One of the most prominent effects of changes in water flux can be seen during the low flow (baseflow) periods, which for a given catchment largely is regulated by the amount of water stored in the catchments. In high latitude and altitude regions with long winters, winter baseflow quantities are primarily reliant on the factors conducive to winter snowmelt or direct contributions from rain on snow. In contrast, summer low flows are often more dependent on water storage and recharge from snowmelt. Previous studies have already shown that snow melts earlier in years with less winter snow accumulation, resulting in earlier peak runoff in the spring (Irannezhad et al., 2022; Venäläinen et al., 2020; Hrycik et al., 2024). Understanding how such changes in winter conditions will affect proceeding seasonal flow is largely reliant on identifying techniques that can detect changes in the duration, magnitude and intensity of the freezing period, and their application towards understanding how catchments' water storage is affected (Blahušiaková et al., 2020; Dierauer et al., 2018).

The techniques of identifying when changes in climate time series occur usually involve using models to detect the statistical departures from historical baselines (Alexander et al., 2006; Reeves et al., 2007; Wilmking et al., 2020). However, monitoring trends in seasonal variables has become increasingly challenging, as traditional definitions of seasonality are insufficient to reflect changes associated with a fluctuating climate. For instance, the most commonly used definitions (e.g. astronomical and meteorological) are static in both time and space (Allen. and Sheridan, 2015; Trenberth, 1983). However considerable changes to transition periods (spring and fall) between the warmest seasons in the summer to the coldest season in the winter are often not adequately defined based on their spatiotemporal variability (Huschke, 1959). As such, static definitions of seasons are insufficient to properly characterize seasonal timing and length that are also likely to continue to change. Currently, many indicators of seasonality changes are based on temperature-related impacts on ecosystems, and hence they provide estimates of changes in the seasonal timing of the growing season. Minimum, mean, and maximum daily temperature have been taken as the most important temperature characteristics in the analysis of climate change (Moberg et al., 2006; Cohen et al., 2014; Cassou and Cattiaux, 2016). Various indices have been used in the literature to divide seasons, such as those based on temperature (Alexander et al., 2006; Hekmatzadeh et al., 2020) and phenology (Cleland et al., 2007; Schwartz and Crawford, 2001; Peng et al., 2013), or moving average smoothing techniques to identify the time that temperature rises above or fall below long-term mean (Blöschl et al., 2017; Park et al., 2021), or defined thresholds such as the 75th and 25th percentile to identify the coldest and warmest periods (Zschenderlein et al., 2019). These studies suggest that the onset and offset of seasons depend on the geographical location of the study region and its specific purpose where a variable threshold should be used for determining the season onset/offset.

Another powerful technique for assessing changes in stream flow involves using the differences in the water isotopic signatures of δ^{18}O in precipitation across seasons (Allen et al., 2019). The strong seasonality in δ^{18}O isotopes with more depleted (lighter) isotopes in winter and enriched (heavier) in summer precipitation presents the possibility to trace the fraction of water arriving as snow in the winter that can either be potentially stored in the catchment or becomes streamflow in the current or proceeding seasons. Similarly, in the summer, the precipitation can be traced to contribute to either storage, streamflow or evapotranspiration (ET). Characterizing the partition of precipitation is therefore important for quantifying the amount of water available for recharging different hydrological storages for sustained stream flow in proceeding seasons.

In this study, we focus on understanding how long-term changes in temperature and precipitation affect baseflow runoff in a snowmelt-dominated boreal catchment during the winter and summer. To do this, we used a 40-year time series of climate data, placed in a 130 year context from a nearby station, to evaluate climate change-related trends. A shorter more detailed time series (30 years) was used to detect potential changes in extreme climate indices during the winter and summer. Winter and summer seasons were thermally defined (Contosta et al., 2020), which is in line with techniques used around the Baltic regions for assessing seasonal climate changes (Ruosteenoja et al., 2015; Kejna and Pospieszyńska, 2023). We hypothesized that warmer winters with shorter duration periods below freezing (zero °C) would result in higher runoff during winter but exhaust the amount of water needed to sustain base flow in the proceeding summer. The isotope analysis of δ18O in winter and summer precipitation was then used to corroborate the findings of the relative contributions of summer and winter precipitation to stream flow.

2 Methodology

The Krycklan Catchment and Svartberget

This study focuses on the Krycklan catchment, which is a research infrastructure that has been monitored since the 1980s (Laudon and Sponseller, 2018). It is located in northern Sweden's boreal zone, approximately one hour from the city of Umeå. Nested within the Krycklan catchment is the Svartberget catchment (C7), which has the longest monitoring high-quality record in the region (Laudon et al., 2021). The 47 ha of C7 is dominated by forest (81%), primarily Noway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) on till soils and peatland (19%). The location of Svartberget represents the conditions in Scandinavian boreal forests and is part of a network of stations within the Integrated Carbon Observation System (ICOS) - a European research infrastructure established to quantify and understand the greenhouse gas balance of the European continent and adjacent regions (Chi et al., 2020).

Meteorological measurements and data

Precipitation and temperature data from the Svartberget field station (Hygget) was obtained from the SITES data portal (https://data.fieldsites.se/portal/). Precipitation (mm) was determined using daily (00-24) accumulated rain and snowfall amounts from manual measurement using a standard Swedish Meteorological and Hydrological Institute (SMHI) gauge with a windshield located 1.5 m above the ground (Climate monitoring program at SLU experimental forests and SITES Svartberget) (Laudon et al., 2013). The data available for Svartberget included two time periods (1982-2022) which consisted of daily mean precipitation and temperature used to detect long-term trends and (1992-2022) which consisted of average daily temperature, average daily minimum and average daily maximum temperature needed for the extreme climate change indices detection. Average daily minimum and maximums represent the coldest and warmest temperatures recorded in a day, aggregated from 10-minute interval recording of temperatures. Included in this work, we have also used a much longer-term dataset (1891-2004) from the SMHI meteorological station in Stensele which is located approximately 150 km west of the Krycklan catchment. The Stensele dataset is used to place the observed trends in the past 40 years in the Krycklan catchment into a more long-term context.

Runoff measurements and data

Runoff measurements from the Svartberget catchment (C7) were done using a field-based recording of hourly stage height and established rating curves to calculate the daily discharge from a weir located in a heated hut. The rating curve was established using the salt dilution technique and bucket-method measurements (Laudon et al., 2004). Occasional missing data were gap-filled using the HBV model (Karimi et al., 2022). The data available extended across 40 years from 1982-2022 which was used in the seasonal analysis to determine the low flow quantities.

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Seasonal definitions

Seasons were separated according to the thermal threshold definition (Contosta et al., 2020) as the consistent frozen period or the period below 0 °C which was longer than seven consecutive days without exceeding 0 °C for a longer period. We used the SMHI 10°C threshold for the definition of summer defined as the period when the daily mean air temperature was above 10°C for longer than five consecutive days without becoming colder again (less than 10°C for more than 5 days). Summer ended mean air temperature fell below 10°C for more than five consecutive days. The spring period between winter and summer was classified as the period when air temperature was above 0°C for more than seven consecutive days but less than 10°C for more than seven consecutive days. The autumn season was not used in this study.

Extreme climate indices

To understand the variability in seasonal extremes, 27 climate change indices which was developed by the World Meteorological Organization (WMO) Expert team of Climate Change Detection and Indices (Donat et al., 2020) was used in this study. These indices assesses various aspects of temperature and precipitation variability including: i) intensity, ii) duration, and iii) frequency of events. The indices identified were then determined for each seasonal blocks (winter, spring and summer (Table S1)) and used in the regression analysis to understand the relation to runoff.

Temperature and precipitation extreme climate indices

Temperature intensity was assessed using seven variables from the daily average, minimum and maximum temperature time series as follows: (i) the coldest daily maximum temperature (Min Tmax), (ii) the coldest daily minimum temperature (Min Tmin), (iii) the warmest daily maximum temperature (Max Tmax), (iv) the warmest daily minimum temperature (Max Tmin), (v) the mean difference between daily maximum and daily minimum temperature (diurnal temperature range), (vi) the number of days when Tmax < 0°C (icing days), and (vii) the accumulated degree days below 0°C (AFDD<0). The duration of extreme periods of the seasons were categorised as (i) the number of days with at least six consecutive days when Tmin < 10th percentile (cold spell), and (ii) the number of episodes with at least six consecutive days with Tmax > 90th percentile (warm spell). The frequency of events within each season was identified as; (i) the percentage of days when Tmax < 10th percentile (cool days), (ii) the percentage of days when Tmin < 10th percentile (cool nights), (iii) the percentage of days when Tmax > 90th percentile (warm days), (iv) the percentage of days when Tmin > 90th percentile (warm nights), and (v) the number of days when Tmin < 0°C (frost days; Table S1).

The intensity, duration, and frequency of seasonal precipitation patterns were determined to also highlight extremes across the years. Precipitation intensity was measured using; (i) maximum 1-day precipitation total, (ii) maximum 5-day precipitation total, (iii) sum of daily precipitation > 95th percentile (wet days), and (iv) sum of daily precipitation > 99th percentile (very wet days) while duration of precipitation events were done using (i) the maximum number of consecutive wet days (precipitation >1 mm) and (ii) the maximum number of consecutive dry days (precipitation).

Analysis: Trend detection and regression analysis

First, the trend detection package in R Core Team (2021) was used to detect trends and significant changes in the long-term dataset of average daily temperature, daily precipitation and daily runoff (1982-2022). Then a seasonal analysis of the significant trends in the winter, spring and summer seasons, was done using the 27 indices defined for each season, individually. Seasonal trends in baseflow (minimum Q) from winter and summer were also examined. The coefficient of regression (r^2) was used to identify the direction of the trends and the p-value was used to determine the significance of the changes. To determine which of the significant extreme climate indices could explain the baseflow during winter and summer, we used a stepwise linear regression analysis in Minitab® Statistical Software 2021 to predict how the previous seasons' significant indices affected seasonal baseflow runoff. For winter, we used the significant variables for temperature and precipitation of the winter season. For summer we used the preceding seasons which included significant variables from winter, spring, and summer to predict summer baseflow runoff.

δ^{18}O and Seasonal Origin index

As a verification test for understanding the contributions of seasonal precipitation to annual runoff, the analysis of δ^{18}O isotopes was done. Samples were collected at regular intervals from 2002 to 2022 in precipitation (n=1930) and stream water (n=821). Precipitation sampling was done manually using national standard precipitation gauges with a windshield where samples were collected in dark glass bottles with a hermetic lid to minimize evaporation during storage. These rain gauges were heated during winter to avoid snow accumulation in the collection funnels and enable sampling during the frozen period. Stream water samples were collected weekly with more frequent sampling during the snowmelt season in similar bottles as precipitation samples. During the winter, a heated weir house enables sampling throughout the frozen season. Both precipitation and stream samples were analyzed using a Picarro cavity ringdown laser spectrometer (L1102-i and L2130-i after September 2013) and the vaporizer module (V1102-i and later the A0211) (See Peralta-Tapia et al. (2016) for more details). Calibration of the isotopic signatures of water was done using internal laboratory standards calibrated against three International Atomic Energy Agency (IAEA) official standards, the Vienna Standard Mean Ocean Water (VSMOW), the Greenland Ice Sheet Precipitation (GISP) and the Standard Light Antarctic Precipitation (SLAP) (Coplen, 1995).

The δ18O data was then used in the seasonal origin index analysis to test whether winter or summer precipitation is overrepresented in annual streamflow (Allen et al., 2019). The SOI show the deviation of annual average discharge from annual precipitation and scales the deviation by the strength of the seasonal signals using eq.1

$$\mathrm{SOI}_{\overline{Q}} = \begin{cases} \dfrac{\delta_{\overline{Q}} - \delta_{\overline{P}}}{\delta_{P_S} - \delta_{\overline{P}}} & \text{if } \delta_{\overline{Q}} > \delta_{\overline{P}} \\[2ex] \dfrac{\delta_{\overline{Q}} - \delta_{\overline{P}}}{\delta_{\overline{P}} - \delta_{P_W}} & \text{if } \delta_{\overline{Q}} < \delta_{\overline{P}} \end{cases} \qquad \text{eq.1}$$

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Where δ_{P_S}, δ_{P_w}, $\delta_{\bar{P}}$ and $\delta_{\bar{Q}}$ represents the δ18O values of summer, winter, and volume-weighted annual precipitation in the C7 catchment and annual volume-weighted mean streamflow δ18O respectively. To determine the SOI of winter and summer, we calculate the SOI of individual streamflow samples $\delta_{\bar{Q}}$ using their individual isotope ratios. The January samples were used to represent the winter and the July samples were used to represent the summer isotopic signals. Linear regression was then used to show the trend in SOI across time for winter and summer where positive $SOI_{\bar{Q}}$ (closer to 1) in the summer indicates a larger fraction of summer precipitation in streamflow. Similarly, increasing negative $SOI_{\bar{Q}}$ (closer to -1) during the winter means greater contributions from winter precipitation to stream flow.

Results

Trends in temperature, precipitation and runoff in Svartberget

In the last four decades, the increase in temperature has accelerated by 2.2 °C where average daily temperatures changed from 0.5 °C in 1980 to 3.1 °C in 2022 across the Svartberget dataset (Fig. 1 A). Placing these trends into a much longer perspective by using a time series that extended to 1892 from the nearby SMHI-Stensele meteorological station, we note that the increasing trends observed in the Svartberget is part of the much longer-term temperature trend that extends over a 100 years. Looking back at the 30 year normal period trends over this time period, we can observe that at the beginning of the century, 1892-1929 annual average air temperature was much colder (-0.5 °C) than the more recent periods (Fig. 1 A).

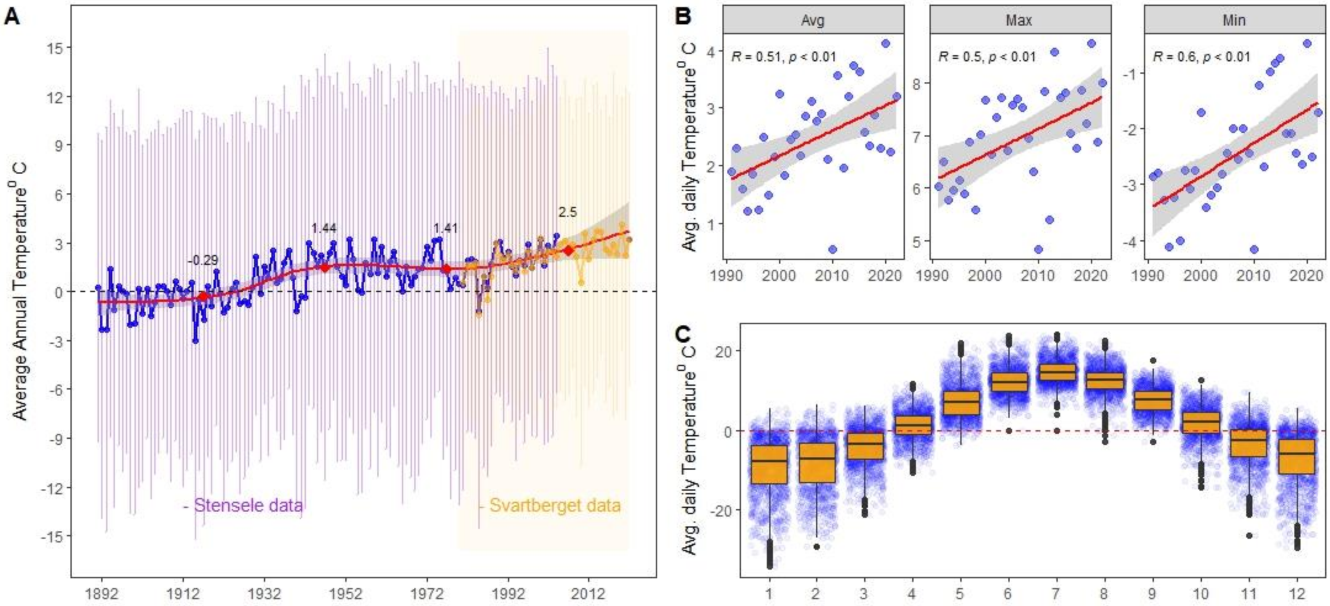

Figure 1 Trend in long-term climate in the Krycklan catchment annually in relation to the much longer-term trend based on SMHI-Stensele data (1891-2004) (A), variability in daily temperatures in the months across the year (B), trends in average annual air temperature, maximum (Max) annual air temperature and minimum (Min) daily temperatures (C) across 30 years from 1992-2022. Purple and orange error bars in panel A represent the standard deviation in the dataset, and blue jitter dots in panel B represent daily average temperatures in Svartberget. Red dots indicate the average within a 30-year period from 2022 backwards in panel A.

A closer look at the last 30 years of variability in temperatures in the Krycklan catchment (1992-2022) showed annual average temperatures ranging from 0.5 to 5 °C across the years increasing from 1.9 °C in 1992 to 3.2 °C by 2022 (Fig. 1B). The annual average minimum temperature ranged from -4.1 to -0.4 °C with the coldest average monthly temperatures occurring in January ranging from -18.7 to -6 °C (Fig. 1C). There is a significant increase in minimum temperatures from 1992 to 2022 -3.4 °C to -1.6 °C indicating an increase of 1.8 °C during the coldest month (Fig. 1B). These changes in minimum temperatures suggest that the winter seasons on average are becoming warmer. Annual average maximum temperatures ranged from 4.8 to 8.7 °C with an increasing trend from 6.4 °C in 1991 to 7.8 °C in 2022 also showing an increase in maximum temperature of 1.4 °C across the 30 years. Warmest periods occur during month 7 (July) when the temperature ranges from 17.4 ° to 25.2 °C (Fig. 1C). Trends in average daily temperatures showed significant increases in observed annual averages ($r^2=0.26$, $p<0.05$), average daily minimums ($r^2=0.36$, $p<0.05$) and average daily maximums ($r^2=0.26$, $p<0.05$) during the period 1992-2022 (Fig. S1).

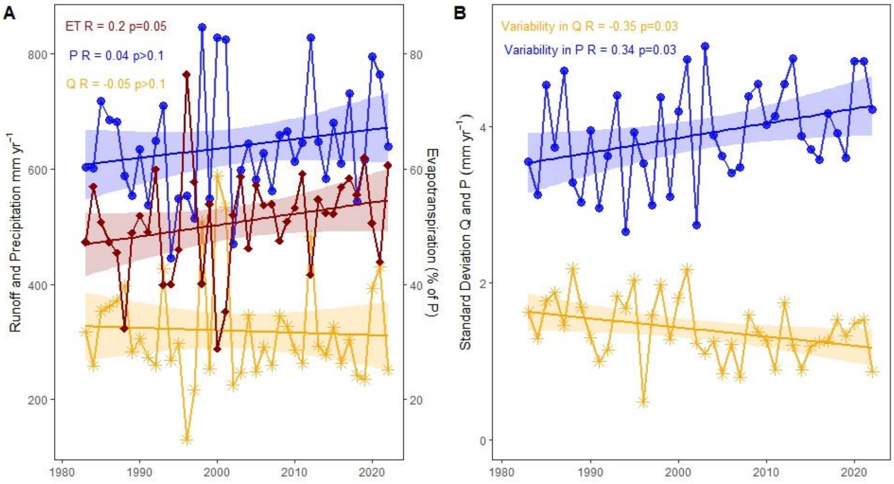

Figure 2 Variability in annual precipitation and runoff from the Krycklan catchment across 40 years showing the differences in the percentage of precipitation that represents evapotranspiration (ET) (A). The variability in runoff (Q) and precipitation (P) during the time period is shown (B).

The long-term trends in daily precipitation from 1982-2022 showed a decreasing trend while runoff increased when fitted with a linear regression (Fig. 2A). A closer look at the variability in both precipitation and runoff across the time series indicated that trends in the daily values were variable across the years decreasing in the period 1982-1997 followed by an increase towards 2022 (Fig. S2). Annually, on average the highest total monthly precipitation occurred in July (86 mm on average across the years) while the lowest occurred in April (28 mm). The annual average precipitation was 650 mm per year with the lowest records occurring in 1994 and 2002 (446 and 470 mm respectively) (Fig. 2A) when July/August precipitation was less than 30% of the long-term July/Aug values. The average total runoff was 318 mm year^{-1} with the lowest runoff occurring in February (5.8 mm month^{-1}) and the highest in May (spring flood) with 96 mm month^{-1} accounting for 30% of the total annual runoff. While no significant trends in annual precipitation and runoff could be detected, ET during the same period calculated from the differences between precipitation and runoff showed a generally increasing annual trend (Fig. 2). It should be noted that the variability in runoff has decreased by 0.5 mm day^{-1} from 1.6 mm day^{-1} to 1.1 mm day^{-1} between the periods of 1982-2022 (Fig. 2B, Table S2, Fig. S2).

Variability in winter and summer climate variables

The significant changes in minimum and maximum annual temperatures prompted further investigations into the variability of temperature and precipitation during the coldest (winter) and warmest (summer) seasons. To do this, we isolated the freezing period by classifying winter as the period when the average air temperature consistently is below zero, and the summer season as when the average air temperature increases above 10ºC consistently for summers (Fig. S3). The temperature trends in Svartberget during the winter and summer are consistent with the longer-term time series from the SMHI-Stensele dataset (Fig. 3A and B). The analysis showed significant increases in average winter temperatures where daily averages ranged from -30.7 ºC to 6.1 ºC with the coldest winters occurring in 1986 and 2010 (with average winter temperatures of -11 and - 9.5 ºC) while the warmest winters in 2014 and 1992 (average winter temperatures -3.7 ºC and 3.2 ºC) (Fig. 3C). The duration of the winter period changed from 171 days to 140 days over the 30 years showing a loss of 31 days with the start of winter shifting 16 days later and ending 15 days earlier (Fig. 3D and E). Summers on the other hand, while showed warmer average temperature trends ($r^2=0.05$, $p=0.14$), the analysis indicated that the season was getting longer (22 days) moving from 80 days in early 1982 to 102 days in 2022 (Fig. 3D and F). The start and end of summers were shifting on average twelve days earlier and later respectively (Fig. 3F). Total precipitation during winter has decreased but increased during the summer, however, neither of these trends was significant $p<0.05$ (Fig. S4).

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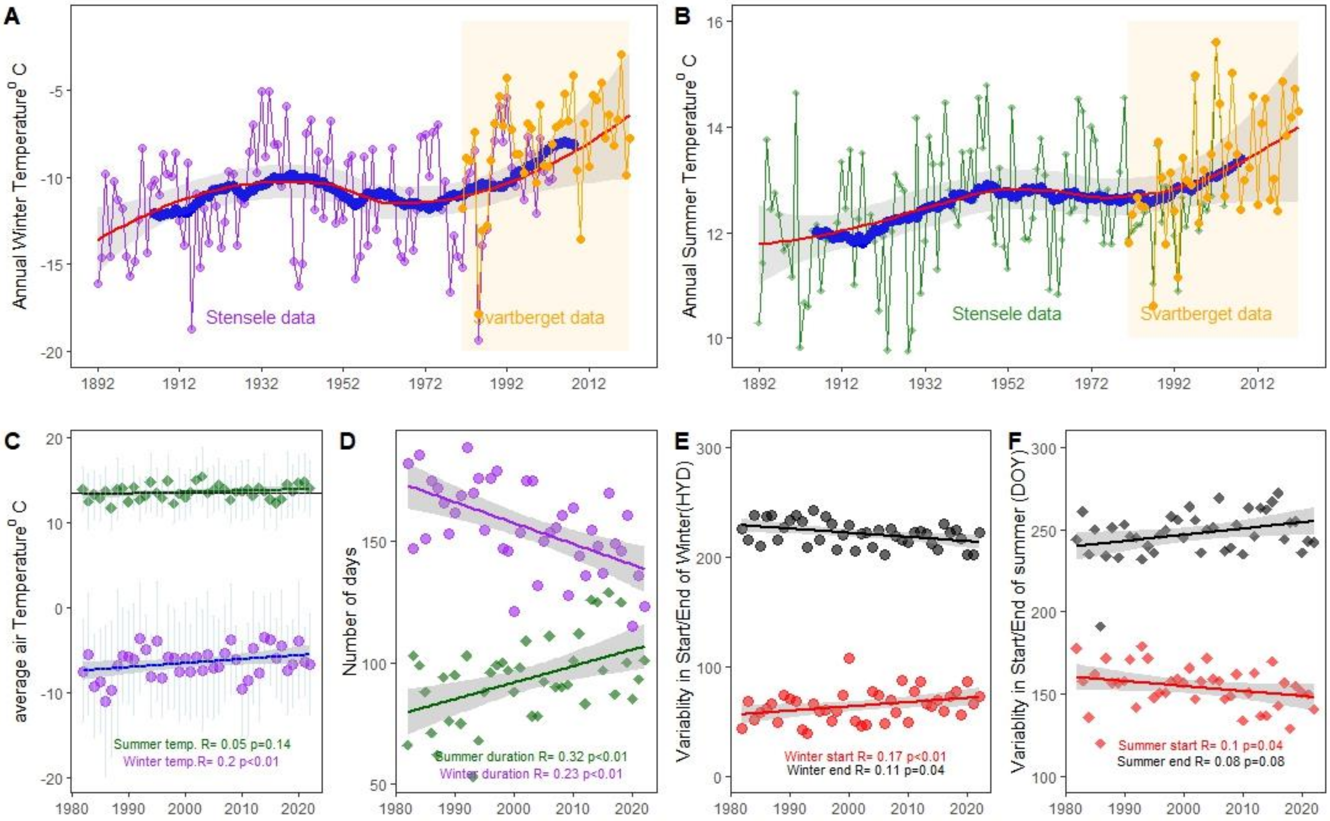

Figure 3 Variability in seasonal temperature across 40 years in the Svartberget Krycklan catchment (blue box) showing changes in temperature during the winter (A) and Summer (B) in relation to the SMHI Stensele longer-term dataset (1891-2004). The variability in annual air temperature and duration are shown in panels C and D for winter (purple) and summer (green). Changes in the start (red) and end (black) of the winter (circle) and summer (diamonds) are depicted in panels E and F respectively.

Extreme climate indices

Trends in extreme indices during the winter suggest that winters are becoming warmer with significant increases in minimum temperatures (Tmin, MinTmin, Diurnal temperature range, AFDD <0, Cold spell duration indicator, Cool nights, and Frost days) (Table S1). The extreme climate change indices during spring showed no significant trends ($p > 0.05$) across the 30-year period. Analysis of summer seasons showed significant increases in the Max Tmax (warmest average daily maximum temperatures) ($p < 0.05$), growing season length, warm days, and warm nights (Table S1, Fig. S5).

Variability in seasonal runoff data

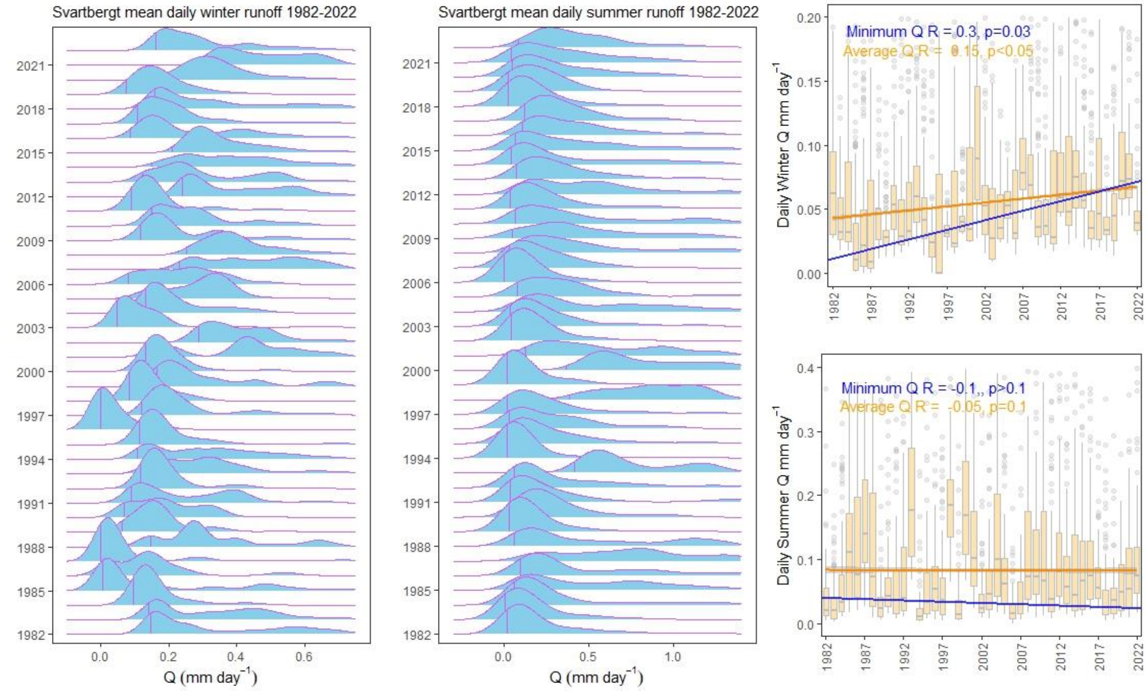

Figure 4 Variability and trends in runoff from the C7 catchment across the winter and summer seasons showing annual variability (orange) across the time period and trends in daily runoff across the seasons.

Winter runoff over the last 40 years showed an increasing trend in minimum runoff ($r^2 = 0.3$, p=0.03) suggesting higher winter baseflows from 1982 to 2022. Runoff during the winter varied between 0.001-0.05 mm day^{-1} per day with total season runoff during the winter varying between 18 mm day^{-1} and 144 mm day^{-1}. On average runoff ranged between 0.1 mm day^{-1} and 1.1 mm day^{-1} per day with the lowest runoff recorded in 1996 and the highest runoff occurring in 2007 (Fig. 4). During the summer, the minimum trends in runoff were also decreasing (r^2=-0.05, p=0.14) with average daily runoff varying from 0.13 mm day^{-1} to 2.45 mm day^{-1}. Daily minimums varied from 0.01 mm day^{-1} to 0.42 mm day^{-1} while maximum runoff during the summers varied from 0.8 mm day^{-1} to 21.9 mm day^{-1}. The driest years were recorded in 2006 (0.03 mm day^{-1}) and the wettest years were recorded in 1986 (0.46 mm day^{-1}) (Fig. 4).

Model of changes in runoff

To understand which hydroclimatic variable was driving the runoff during seasonal low flow periods, we use a stepwise linear regression analysis to identify the best explanatory climate variables of the preceding season for runoff in Minitab Statistical Software 17. A trend detection test was first performed in R to determine if there was a significant trend in each seasonal data set. Only the extreme climate variables that showed a significant trend were used in the seasonal runoff regression models.

From this analysis, we found that the accumulated degree days below zero (AFDD<0) were the best explanatory variable of minimum runoff during the winter (r^2=0.44 p<0.05). The analysis showed that winters with fewer AFDD<0 (warmer winters), were associated with higher winter baseflow while more ACDD<0 (cold winters) showed low winter baseflow (Fig. 5). The best explanatory factor of runoff variability in summer baseflow was a multivariate model which included winter variables AFDD<0 and MaxTmax (r^2=0.45 p<0.05) as found from the stepwise linear regression model. The three years (1993, 1998 and 2000) were the largest outliers in the model because these were the wettest years when minimum runoff was above 0.35 mm day^{-1} (Fig. 5B).

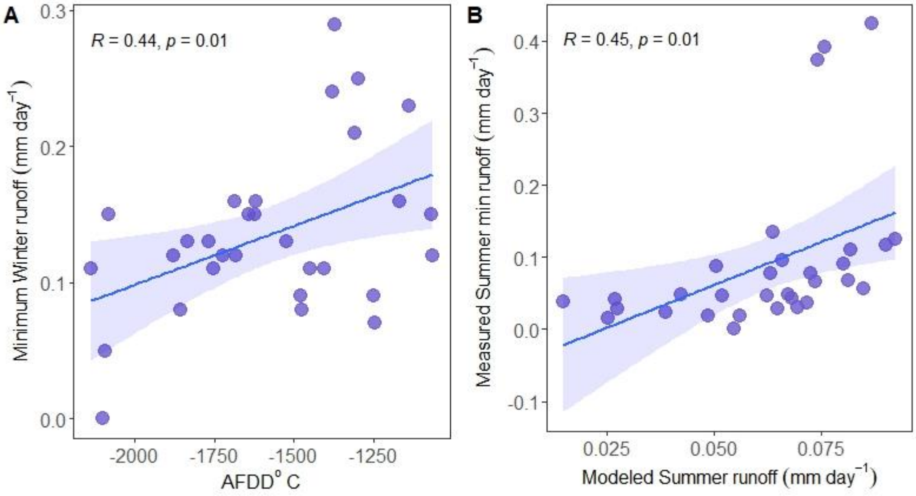

Figure 5 The best explanatory climate indices of winter baseflow were the accumulated freeze degree days below zero (AFDD<0) (Qw=1.26 - 0.0065 AFDD <0) for the winter and the summer (Qs= 0.3 - 0.007 Summer Max Tmax + 0.00004 Summer AFDD <0)

Isotope analysis using season origin index (SOI)

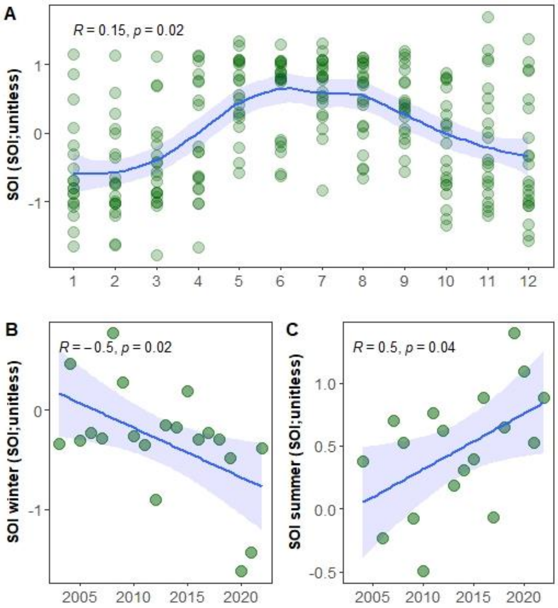

Figure 6 Variability in season origin index (SOI) daily values from 2003-2022 in the C7 catchment with a loess curve (blue) representing average monthly SOI values (A). The fraction of midwinter precipitation and midsummer precipitation that becomes stream flow each year is shown in panels B and C fitted with linear regression.

Investigating the SOI in the C7 catchment showed strong seasonality across the year when looking at monthly variability. In the colder months, SOI averaged -0.5 in December, January and February while in the warmer months, averages increased to 0.5 in June, July, and August. A closer look at the winter SOI in January showed that a greater fraction of the winter precipitation was represented in annual stream flow across time as indicated by the SOI values shifting closer to -1 (typical of mid-winter precipitation) (Fig. 6B). The SOI in the summer (July) increased with a shift closer to 1 (typical of midsummer precipitation) indicating that a larger fraction of summer precipitation in later years became stream flow relative to the total annual precipitation suggesting a shift away from the mid-winter signal (-1) (Fig. 6C).

Discussion

Analysis of extreme climate indices over the past 40 years in the boreal Krycklan catchment has shown most pronounced changes occurred in the winter where warmer winters with less precipitation as snow have increased baseflow runoff quantities during the winter, which resulted in an exhaustion of water left for baseflow in the proceeding summers. The changes in runoff during the winter and summer are also supported by isotope analysis that shows an increasing contribution of winter precipitation to winter runoff and a decreasing contribution to summer runoff. Although the results are based on the 40-year time series, these changes observed are part of a longer-term trend dating back to 1891 from a nearby meteorological station

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(Stensele), which has accelerated in the last decades (Fig 1A, 3A and B). Nevertheless, the 40-year time series of both meteorological and hydrological data allowed studying the effects of changing seasonal hydro-climatic variables on runoff in ways that previously had not been possible. These findings presented in this study suggest that warmer winter climates provide direct feedback on the hydrological flow regime with consequential changes to the seasonal distribution of water in the catchment linked to the inferred change in storage.

During the winter period, large amounts of seasonally stored water in the snowpack regulate catchment water recharge and distribution to streams throughout the year (Trenberth, 2011). In normal winters, the frozen season sustains snowpack until the spring. Our analysis demonstrated that there is a shift towards warmer winters as reflected in eight climate indices (Tmin, diurnal temperature range, AFDD <0, cold spell duration indicator, cool nights, frost days, icing days and snow days) (Fig. S5). These changes are consistent with other winter based studies that shown more frequent and longer warm spells, and decreases in the frequency, duration, and severity of cold spells, based on both observations (Easterling et al., 2016) and model projections (Sillmann et al., 2013). In addition to changes in temperatures, we also found a significant reduction in the number of snow days during the winter. The isotope analysis of δ^{18}O was then used to verify whether the increases in winter base flow were caused by direct winter precipitation using the SOI. The results showed that over time (from 2002 to 2022), SOI values decreased (trending from 0.2 in 2002 to -0.6 in 2022 on average), showing a shift towards winter precipitation signal confirming an increased contribution from winter precipitation to stream flow (Fig. 6B). Together, these results all suggest that the warmer winter trajectory could further enhance mid-winter melt events, rather than being stored in place as snowpack until spring melt, which leads to higher flows in streams during the frozen season.

Modelling the baseflow runoff during the winter using a stepwise linear regression showed that the best predictor was the accumulated degree days below zero (AFDD<0) which illustrated that warm winters with lower AFDD<0 had higher winter baseflow compared to the years with the colder winters with more AFDD<0. These results can be explained by the reduction in the amount of precipitation falling as snow during a shortened frozen season, increase in the frequency of mild (>0 °C) periods and/or induce earlier snowmelt as suggested by (Laternser and Schneebeli, 2003), while harsher winters produce deeper snow cover and delayed snowmelt (Rixen et al., 2022; Bokhorst et al., 2016). A similar increase in winter runoff has also been recorded in Finland (Rutgersson et al., 2022; Kasvi et al., 2019) and in southern Sweden, with earlier lake ice break-up (58 %) between 1913–2014 (Arheimer and Lindström, 2015; Hallerbäck et al., 2022). The consequence of warmer winters have already been found to reduce soil frost (Friesen et al., 2021; Girardin et al., 2022; Easterling, 2002), alter stream runoff and timing of proceeding springs (Breton et al., 2022; Blöschl et al., 2017). However, future changes in the magnitude and intensity of flooding caused by rapid snowmelt due to warmer winters could increase economic uncertainties for vulnerable areas and infrastructures (Tabari, 2020; Nasr et al., 2021) should these events become more prevalent.

The best model of summer baseflow was a multiple regression of three indices (Winter AFDD<0 and Summer MaxTmax) (r^2=0.45 p<0.05) (Fig. 5B) indicating that both warmer winters and summer conditions (warm and dry) affected low runoff in the summer. This is in line with previous research that showed the importance of antecedent hydro-climatic conditions in explaining the inter-annual variability in summer flows (Earman et al., 2006; Beaulieu et al., 2012; Van Loon and Laaha, 2015; Dubois et al., 2022; Kinnard et al., 2022). To verify whether the decreases in summer runoff were due to the reduced contribution from winter precipitation, we used the SOI analysis of δ^{18}O which showed a greater contribution from summer precipitation to stream flow across time (from 2002-2022) (Fig. 6B). The trajectory of increasing summer precipitation in the isotopes analysis to streamflow therefore infers that there is reduced contribution of catchment water storage from the previous winter. The physical mechanism that facilitates this could be related to the rain-on-snow and/or mid-winter snowmelt where a greater proportion of snow melts, which shifts the seasonality of winter streamflow to an enhanced winter precipitation signal (Fig. 6A) resulting in less water available for aquifer recharge as seen across other cold regions (Jenicek et al., 2016; Teutschbein et al., 2022; Boumaiza et al., 2020). With the higher rates of evapotranspiration observed across the years, warm winters together with high summer temperatures, intensify the magnitude of low flows in boreal catchments. While these findings highlight the vulnerability of groundwater resources in Fennoscandia to changes in winter and summer climate conditions, it call for a deeper understanding of how the changes in the magnitude, intensity and frequency of other hydrological events will be affected in the future.

The findings from this research highlight the susceptibility of boreal catchments to climate conditions when winter warming coincides with summer warming and low summer precipitation. This leads to a higher risk of hydrological droughts where deficits in both surface and subsurface water occur resulting in stronger impacts on biophysical conditions and biogeochemical processes (Teutschbein et al., 2022; Bouchard et al., 2024; Blahušiaková et al., 2020), and hence aquatic organisms (Kreyling et al., 2019; Williams et al., 2015). During the low flow regime, the strong control of stream temperature affects life in aquatic ecosystems as well as the water availability for drinking and irrigation purposes, exacerbating low reservoir levels and decreasing hydropower generation (Dierauer et al., 2018). Other implications of warmer winters and summer processes have already been shown to affect net ecosystem exchange (NEE) (Monson et al., 2005), water table depth (Dao et al., 2024; Nygren et al., 2021; Dubois et al., 2022), ecological processes (Hrycik et al., 2021), and tree growth decline (Laudon et al. 2024). While higher winter baseflow moderates spring peaks and the risk of flooding (Blöschl et al., 2017; Irannezhad et al., 2022), the lower recharge to groundwater can result in drier summer landscapes with indirect consequences such as increased wildfire activity (Westerling et al., 2006), higher rates of tree mortality (Sterck et al., 2024), increased water stress on mountain ecosystems (Hatchett and Mcevoy, 2018) and decreased uptake of carbon (Van Der Woude et al., 2023). Ultimately, the implications of warmer winters on proceeding seasonal runoff can be severe and warrant additional efforts in preparing for future climate changes.

Conclusion

Our long-term dataset showed that dominant hydrometeorological characteristics of the boreal Krycklan catchment are changing with consequences for the catchment hydrology. Enhanced extreme climate indices during summer and winter suggest warming in both seasons. Warmer temperatures will result in shrinking snowpacks that melt earlier in the year causing the effective storage capacity of winter snowpacks to decrease. We show that warmer winters already have, and will continue to result in decreased catchment water storage due to increased winter runoff before the occurrence of the true spring freshet, which exhausts the potential for maintaining summer base flow. These findings have been supported by trends in isotopic composition suggesting changes towards winter precipitation dominating winter stream flow while summer precipitation signals dominate summer flows. This research highlights the importance of understanding future hydro-climatic changes where changes in the seasonal distribution of water could magnify floods or low flow conditions, as well as other drought-related issues in light of future climate change.

Code Availability and Data Availability

Runoff data, meteorological data and isotopes data for Svartberget can be download from the SITES data portal (https://data.fieldsites.se/portal/). Long-term data from the Stensele station can be obtained from SMHI achieves. Codes used in the production on graphs and their associated files can be found on fig.share.com https://doi.org/10.6084/m9.figshare.27320538

Author contribution

HL developed the initial concept, assisted in the analysis of results, and discussion. TT processed the data, analysed the results and wrote the first draft of the manuscript.

Competing interest

The contact author has declared that none of the authors has any competing interests.

Special issue statement

This article is part of the special issue “Northern hydrology in transition – impacts of a changing cryosphere on water resources, ecosystems, and humans (TC/HESS inter-journal SI)”. It is not associated with a conference.

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