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Key Points:
- Snow cover control of boreal hydrology appears at a certain snow/precipitation zone
- Catchment characteristics are relatively more important for southern than for northern and midboreal zone low flows
- Peatland drainage decreases catchment storage and low flows during both summer and winter

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2
- Table S3
- Table S4

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Snow to Precipitation Ratio Controls Catchment Storage and Summer Flows in Boreal Headwater Catchments

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Abstract Catchment storage sustains ecologically important low flows in headwater systems. Understanding the factors controlling storage is essential in analysis of catchment vulnerability to global change. We calculated catchment storage and storage sensitivity of streamflow for 61 boreal headwater catchments in Finland. We also explored the connection between computed storage indices and low flow conditions. The relationships between selected climate, snow, and catchment characteristics and calculated storage properties and low flows were investigated, in order to assess the importance of different factors that render catchments vulnerable to climate and environmental change. We found that the most sensitive areas to climate change were located in the southern boreal coastal zone, with fine-grained soils and agricultural areas. In contrast, catchments in the middle and northern boreal zone, with till and peatland soils and higher snow water equivalent values, were less sensitive under current conditions. In addition, we found a threshold at a snow to precipitation ratio of 0.35. Above that threshold, summer low flows were generally sensitive to changes in snow conditions, whereas below that threshold catchment characteristics gained importance and the sensitivity was more directly related to changes in temperature and timing of rainfall. These findings suggest that a warming climate will have pronounced impacts on hydrology and catchment sensitivity related to snow quantity and snow cover duration in certain snow to precipitation ratio zones. Moreover, land use activities had an impact on storage properties in agricultural and drained peatland areas, resulting in a negative effect on low flows.

1. Introduction

Boreal forest is one of the largest biomes in the world, with global-scale impacts on water cycles and the carbon and energy balance (Bonan et al., 1992; Dixon et al., 1994; Gauthier et al., 2015). Climate change is predicted to have strong effects in the boreal region (Laudon et al., 2017; Ruckstuhl et al., 2008), including a shift from snowfall to rain (Berghuijs et al., 2014) and earlier melting of the snowpack in spring (Stocker et al., 2013; Woo et al., 2007). These changes will have a great influence on snow-dominated boreal hydrology and alter catchment water storage properties by increasing discharge during the winter recession and changing the timing and magnitude of groundwater recharge during the spring freshet (Blöschl et al., 2017; Jenicek et al., 2018). This, together with direct human actions such as deforestation (Sorensen et al., 2009) and peatland drainage (Holden et al., 2004; Prévost et al., 1999), can have considerable consequences for ecologically important summer low flows (Poff et al., 1997), water security (Castle et al., 2014), and water quality (Kelly et al., 2016; Price, 2011). Thus, evaluation of the resilience of streamflow to changes in climate and land use is critical for water resources management.

Climate is typically the first-order control in the streamflow regime (Devito et al., 2005). In addition, catchment physiographical and vegetation characteristics have an impact on evapotranspiration, infiltration, water release, and storage properties and thereby mediate the streamflow response (Blöschl et al., 2013; Price, 2011). Both climate and catchment characteristics determine catchment sensitivity to changes, because of simultaneous changes in soils, vegetation, and topography under the influence of climate and slow geological processes, such as weathering and erosion (Blöschl et al., 2013). Small headwater catchments are especially vulnerable to any changes caused by climate or anthropogenic pressures (Finn et al., 2011).

In previous studies, thick glacial till deposits, peatland/wetland areas, forest on sandy soils, and glaciofluvial deposits have been shown to promote water storage and low flows, while shallow till, hummocky moraines, deciduous-mixed wood forest, and open-water wetlands have been shown to have the opposite effect (Buttle & Eimers, 2009; Devito et al., 2017; Karlsen et al., 2016). Payn et al. (2012) found that the impact of topographical contributing area on baseflow decreases during recession, indicating that catchment subsurface properties then gain in importance. Li et al. (2017) showed that summer low flows are significantly influenced by topography in snow-dominated catchments, while Godsey et al. (2014) concluded that summer low flows are strongly dependent on annual peak snow water equivalent (SWE), with a decrease leading to decreased summer low flows. Moreover, Jenicek et al. (2016) showed that during high SWE years, summer low flows occur later and precipitation after maximum SWE has a significant impact on summer low flows.

Only a few studies have explored the combined impact of catchment characteristics and climate on catchment storage properties and related this to low flows (e.g., Staudinger et al., 2017). To our knowledge, no previous study has examined the combined influence of catchment characteristics and climate, in particular snow conditions, on catchment storage and low flows in boreal regions. Peatlands, which have major impacts on hydrology in boreal regions (Bullock & Acreman, 2003), have been widely drained in Finland and other similar regions to increase soil productivity and create conditions suitable for forestry, peat extraction, or agriculture (Holden et al., 2004). However, the complex interactions between peatlands and streamflow are still not fully known at catchment scale (Waddington et al., 2015). Peatland drainage has been shown to both increase and decrease catchment storage and low flows, depending on peatland location and type, natural groundwater levels, and time since drainage operations (Bacon et al., 2017; Holden et al., 2004). Furthermore, no previous study has examined the impact of peatland drainage on catchment storage and low flows using a large data set of boreal catchments.

Hydrological processes are commonly investigated using physically based models (e.g., Frei et al., 2010; Krogh et al., 2017). While such process models are very useful in increasing knowledge of the mechanisms controlling storage and streamflow, they are often laborious to parameterize and solve numerically, which impedes their use in broad-scale studies (Aalto et al., 2018). Empirical techniques rely on statistical associations between response variables and predictors (Hjort & Luoto, 2013). They are being increasingly used in environmental research and show high potential for modeling hydrological process-environment relationships over broad geographical regions. Statistical models are computationally more cost efficient than process models and can readily account for environmental conditions related to soil conditions, topography, and land cover, which can be difficult to parameterize physically (Varanka & Hjort, 2017). However, there are inferential limits associated with observational studies, depending on the characteristics and accuracy of the data sets used. Moreover, spatial covariation in catchment characteristics can hinder the ability to isolate the effects of individual variables. Generalized additive models (GAMs) constitute a flexible family of statistical fitting methods (Hastie & Tibshirani, 1990). GAMs may offer certain benefits due to their greater capacity to reveal complex relationships between runoff and the environment and thus provide more accurate models than conventional regression techniques.

In this study, we calculated the catchment storage and storage sensitivity of streamflow for a unique boreal headwater catchment network and examined the relationship between catchment storage properties and seasonal low flow. We also investigated the role of climate, snow, catchment characteristics, and land use activities, such as agriculture and peatland drainage, and their relative impact on catchment storage properties and low flow, in order to identify catchment elements that can mitigate catchment response to climate change by supporting low flows. The main hypotheses tested were that (H_1) snow increases catchment storage and low flows in the boreal region and (H_2) pristine peatlands increase catchment storage and low flows at catchment scale.

Specific objectives were to (i) analyze the spatiotemporal variability in storage properties and low flows in boreal catchments, (ii) determine possible climate controls on hydrological processes and low flows, (iii) identify important catchment elements for storage and low flows in boreal landscapes, and (iv) study the effect of peatland drainage on catchment-scale storage and low flows.

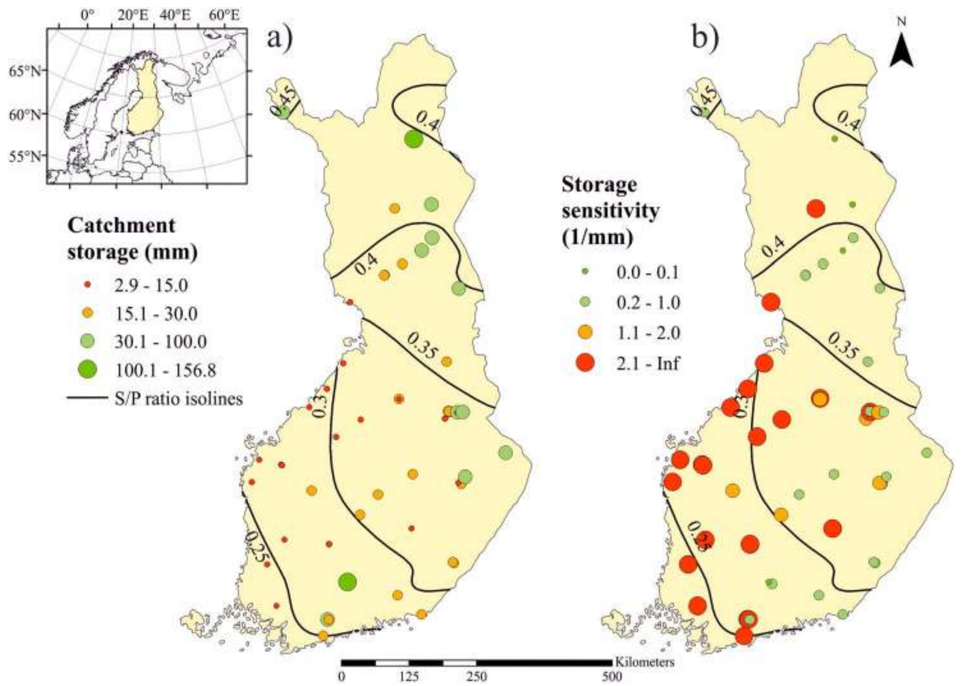

Figure 1. Map of study locations and (a) calculated catchment water storage (S_C) and (b) calculated storage sensitivity (ε_S) for low flow conditions (Q_{85}). Snow to precipitation (S/P) ratio is shown as isolines. Spatial variability of the parameters used for ε_S and S_C calculations is shown in supporting information Figure S1. S/snow to precipitation.

2. Materials and Methods

2.1. Study Catchments

The study was conducted using data on 61 boreal headwater catchments (Figure 1 and supporting information Table S4) that form the national small basins research network in Finland (Seuna, 1983). The area of the catchments ranges from 0.07 to 79.20 km^2 (median 6.15 km^2), while the topography is relatively flat, with mean slope ranging from 1.1° to 12.5° (median 3.1°) and mean elevation from 15 to 557 m above sea level (median 144 m above sea level). The dominant land cover type is forest (median 80% of surface area), followed by peatland (median 26%), while agricultural areas are relatively common in coastal regions in southern and southwestern Finland, where the surface geology is mainly clay and silt. The majority of surface geology in the study catchments is basal till (median 60% of catchment area). Sand/gravel and glaciofluvial deposits (hereafter "sand/gravel soil") also occur (median 0%, mean 6%). The climate in Finland is humid, with mean annual temperature of 5 °C in the south and −2 °C in the north, mean precipitation of 700 and 450 mm, respectively, and mean snow depth by the end of March of 5 and 80 cm, respectively (Pirinen et al., 2012). Many climate and catchment characteristics covary from the coast to inland and from south to north (Spearman correlation matrix; supporting information Figure S2). In particular, clay/silt soils and agricultural areas are positively associated with air temperature (and negatively with snow), while peatlands and till soils are negatively associated with air temperature (and positively with snow). Mean elevation also shows a negative association with air temperature, as the ground elevation increases from coastal areas to inland and from the south to the north.

2.2. Data

Study basins were selected based on availability of long-term runoff, snow course, and potential evaporation (PET) data at the Finnish Environment Institute (SYKE, open Hertta database), covering the maximum period 1958–2015 (supporting information Table S7). Daily precipitation and temperature data were taken from a 10-km × 10-km interpolated grid produced by the Finnish Meteorological Institute (Paituli database). Annual catchment-specific meteorological values were calculated using data from the closest measurement station or interpolated grid points from discharge measurement points. Surface geology was determined using the surface geology map of Finland (resolution 10 m) produced by the Geological Survey of Finland (GTK, open Hakku database) and land use using Corine Land Cover 2012 (resolution 20 m), provided by SYKE (Paituli database). Topographical properties were calculated from a 2-m digital elevation model (excluding six catchments for which only a 10-m digital elevation model was available) obtained from the National Land Survey of Finland (MML, open data). Data on drained and pristine peatland cover (resolution 25 m) were obtained from SYKE. Catchments in which more than 5% of the area was occupied by lakes were excluded from the analysis, as lakes exert strong control over catchment storage and streamflow. Moreover, the maximum catchment area was arbitrarily limited to 100 km^2, to reduce the impact of catchment size and nonuniform land cover types on runoff processes.

Runoff data were gap filled using linear interpolation with a maximum gap of 5 days. Maximum permissible number of missing data in a month was 6 days and in a hydrological year 30 days. If these criteria were not met, the whole hydrological year was omitted from the analysis. The hydrological year used for calculating annual hydrological and meteorological values was October to September.

2.3. Methods

Recession analysis is a well-established method for estimating the shape of the storage-discharge relationship of catchments (Brutsaert, 2008; Brutsaert & Nieber, 1977). There are several other ways to estimate catchment storage, such as water balance and hydrological modeling methods (Staudinger et al., 2017). The strength of the recession analysis is that widely available observations of streamflow integrate the processes within a catchment and can therefore be promising for analyzing the controls of storage and hydrological behavior in a catchment (Kirchner, 2009). However, there are many uncertainties associated with the method; for example, linearity versus nonlinearity of storage, antecedent conditions (Patnaik et al., 2015), and the selected recession technique affects the results (Stoelzle et al., 2013). A recently introduced method for quantifying streamflow sensitivity to storage changes (Berghuijs et al., 2016) can be used to indicate catchment vulnerability to climate and land use changes.

2.3.1. Catchment Storage and Storage Sensitivity

Hydrograph recession analysis (Brutsaert & Nieber, 1977), based on the assumption that terrestrial water storage is the only source of streamflow, was used to determine catchment storage and storage sensitivity of streamflow. Plotting daily streamflow Q (mm/day) and recession rate $\frac{dQ}{dt}$ (mm/day^2) in a log-log graph revealed an approximately linear correlation between the variables, suggesting a power law relationship (equation (1)), which can be used to derive the coefficients α (mm$^{1-\beta}$d$^{\beta-2}$) and β (dimensionless) using linear regression:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -\alpha Q^{\beta} \tag{1}$$

For determining the recession rate $\frac{dQ}{dt}$, instead of the commonly used constant time step method, we used the recently introduced exponential time step (ETS) method (Roques et al., 2017), which was found to increase the robustness of estimates of coefficients α and β. The maximum time interval n in the ETS method was set to 5 days, which was more than 15% of the maximum recession length in the study catchments, as suggested by Roques et al. (2017). However, for our data sets the difference between constant time step and ETS methods was minor, with high correlations (not shown) between the calculated coefficients.

Assuming a linear reservoir model, that is, a linear storage-discharge relationship ($\beta = 1$), catchment water storage S_C (mm) can be calculated as

$$S_C = KQ_{\mathrm{Max\_BF}} \tag{2}$$

where K (=1/α) (day) is the recession constant (Brutsaert, 2008) and $Q_{\mathrm{Max - BF}}$ (mm/day) is the maximum baseflow (Arciniega-Esparza et al., 2017). In order to determine the maximum baseflow, baseflow separation was performed using a digital filter approach (Lyne & Hollick, 1979), implemented in the R {hydrostats} package. Filter parameter value was set to 0.975, which gave a slow response to quick flow peaks and was thus assumed to represent the deep storage component. For direct determination of the origin of the water, geochemistry or stable isotope data would be needed. The median of annual maximum baseflows was used to minimize the impact of exceptional climate conditions.

Storage sensitivity of streamflow ε_S (1/mm), a concept introduced by Berghuijs et al. (2016), is defined as the change in normalized streamflow dQ/Q divided by the change in catchment storage dS

$$\varepsilon_S = \frac{dQ/Q}{dS} \tag{3}$$

which can be further expressed as

$$\varepsilon_S(\alpha, \beta, Q) = \alpha Q^{\beta-2} \tag{4}$$

where Q is the flow rate of interest. We used Q_{85} to calculate the storage sensitivity of streamflow for low flow conditions, as in Berghuijs et al. (2016). In addition to α, parameter β was determined using recession analysis, allowing nonlinear catchment storage-discharge relationships (equation (1)). Because β is determined from recession, parameter α is also different from the catchment storage calculations. We performed a sensitivity test (supporting information Tables S2 and S3 and Figures S3 and S4) for the filter parameter and flow quantile, to analyze the effect of choice of values on the robustness of the results.

The procedure used for recession period selection was adapted from Berghuijs et al. (2016). We used 3-day moving average of the hydrograph, discarded days with more than 0.9-mm precipitation, selected periods of minimum of 7 days of recession, and removed the first 3 days of the recession in order to minimize the impact of precipitation and fast runoff processes. To avoid impacts of evapotranspiration and snowmelt, which were assumed to be negligible (Kirchner, 2009), the recession periods were analyzed for September–December.

2.3.2. Streamflow Characteristics and Climate Parameters

From the daily data sets, the median of annual values was calculated for specific discharge (Q), precipitation (P), temperature (T), PET, maximum SWE (max SWE), day of year for max SWE, and end of the snow cover. Seven-day low flow indices were calculated separately (using the {EflowStats} package in R) for winter (February–March) and summer (July–August) from daily streamflow records for each catchment. The selected months cover the typical timing of low flow conditions during winter due to subzero temperatures and during summer due to high evapotranspiration.

Sensitivity of streamflow to climate was calculated using climate elasticity to precipitation with the contribution of evaporation (Sun et al., 2013)

$$\varepsilon_P = \text{median}\left(\frac{\Delta Q/\overline{Q} - \Delta \text{PET}/\overline{\text{PET}}}{\Delta P/\overline{P} - \Delta \text{PET}/\overline{\text{PET}}}\right) \tag{5}$$

where ε_P is climate elasticity (dimensionless), Q (mm/year) is annual streamflow, PET (mm/year) is annual potential evaporation, and the superscript line denotes long-term average. Class A pan-measurement data from SYKE were used to calculate the annual sum of PET. Dimensionless wetness index P/PET was taken as the median from its annual values. Annual median snow fraction (dimensionless) of total precipitation (snow to precipitation [S/P] ratio) was calculated using 1.1 °C as the threshold for snowfall (Feiccabrino & Lundberg, 2008; Jenicek et al., 2016). See supporting information Tables S5 and S6 for calculated values of hydroclimate parameters.

2.3.3. Relationships Between Storage Properties and Catchment and Climate Characteristics

Because of the strong collinearity (Spearman correlation matrix) of many of the catchment characteristics and climate indices, we performed multivariate principal component analysis to examine the relationships between the predictor variables and to reduce the amount of variables. The catchment characteristics were centered and scaled before conducting the principal component analysis. Significant principal components (PCs) were selected using the broken stick method (Jackson, 1993). The relationship between catchment storage, storage sensitivity, low flows, and the scores from significant PCs reflecting catchment characteristics and climate conditions was analyzed using GAMs, which are extensions of generalized linear models (Hastie & Tibshirani, 1990), implemented in the {mgcv} package in R. The GAM analysis was used to find possible nonlinear relationships, as runoff-generating processes are usually nonlinear. GAMs are highly useful for developing realistic response curves, because they fit smoothers to the data without requiring specification of any particular mathematical model to describe nonlinearity (Hastie & Tibshirani, 1990). In a semiparametric GAM, the linear predictor variable is substituted with an unspecified smooth function estimated using a scatterplot smoother

$$g(\mu) = \alpha + \sum_{j=1}^{p} f_j(x_j) \tag{6}$$

where g is the link function, μ is the expected value of the response variable related to predictor variable x, α is a constant, and f are the unspecified smooth functions. Gamma distribution and quasi-Poisson distribution with a log link function were used in the model fitting for catchment storage and storage sensitivity, respectively. The degree of freedom in fitted models was allowed to vary between 1 (linear relationship) and 3 (nonlinear relationship), to avoid model overfitting. Residual analyses (homoscedasticity and normality test by Kolmogorov-Smirnov) were used to select optimal distribution and link function. For 7-day low flow, a Gaussian distribution with an identity link was used because the threshold behavior observed in scatterplots between S/P ratio and summer 7-day low flow was lost in the Gamma distribution-based GAM with a log link. The goodness of GAMs was analyzed using the leave-one-out cross-validation (LOOCV) approach, by plotting the response curve shapes to the same graphs as the original models and comparing the range of p values and explained deviances between the original models and the LOOCV results. P values were calculated using the {mgcv} package in R, with Wald tests used to test whether the smooth term in GAMs was statistically significant compared with the zero effect in the model. To analyze the spatial patterns and possible pseudo-replication of the catchments in the data, which can generate inference in the statistical analysis (Lennon, 2000), spatial autocorrelation (SAC) in the GAM residuals was calculated as Moran's I, using the {pgirmess} package in R (e.g., Bini et al., 2009; Dormann et al., 2007).

3. Results

3.1. Spatiotemporal Variability of Storage Properties and Low Flows

Catchment storage S_C and storage sensitivity of streamflow ε_S for low flow (Q_{85}) showed considerable spatial variation between the study catchments (Figure 1 and supporting information Table S4). In general, catchment storage increased on moving from the coastal southwest toward the interior northeast of Finland, while storage sensitivity decreased. Both storage indices were directly related (log-log scale) to mean annual 7-day low flows during summer and winter periods (Figure 2). Catchment storage, but not storage sensitivity, had a positive relationship with 7-day low flow, confirming that the hydrograph-derived indices reflect catchment flow characteristics. Summer low flow showed a stronger relationship with the storage indices than winter low flow. The sensitivity analysis for the filter parameter (supporting information Table S2 and Figure 3) used in baseflow calculations showed that the correlation between the S_C values remained high even with a 5% decrease in the filter value, representing the lower filter parameter values usually found in the literature. The results for flow quantile (supporting information Table S3 and Figure 4) showed no sensitivity to changes of ±1% of Q_{85} and relatively low sensitivity to changes of ±5% of Q_{85}. For the higher quantiles (+10% of Q_{85}), the number of zero flows in the daily time series made the analysis difficult, because the quantile value of 0 mm/day resulted in infinite values of ε_S.

3.2. Multivariate Controls for Catchment Storage Properties and Low Flows

The first two principal components (PC1 and PC2) were selected for further analysis based on the broken stick criterion (Table 1 and supporting information Figure S5). PC1 explained 42.1% and PC2 16.6% of the variance in climate and catchment characteristics among the study catchments. The loadings on PC1 (Table 1) suggested that PC1 largely represented the climate and snow conditions, with higher values for PC1 reflecting lower mean annual air temperatures and more snow influence. Additionally, mean elevation, clay/silt soils, and agriculture, followed by pristine peatlands, had relatively high loadings on PC1, revealing their covariation with climate. Mean elevation and proportion of pristine peatlands were positively associated with increased PC1, whereas low values for PC1 were found in catchments with high proportions of clay/silt soils and agriculture. The highest loadings on PC2 (Table 1) were from drained and forested peatlands and mean slope. High values for PC2 were found in catchments with more drained and forested peatlands, and with lower mean slopes, revealing their covariance. Forest on mineral soil had a moderate loading in PC2, with a higher proportion at lower values of PC2. Standardized catchment scores and loadings from climate and catchment characteristics are shown as a biplot in supporting information (Figure S5).

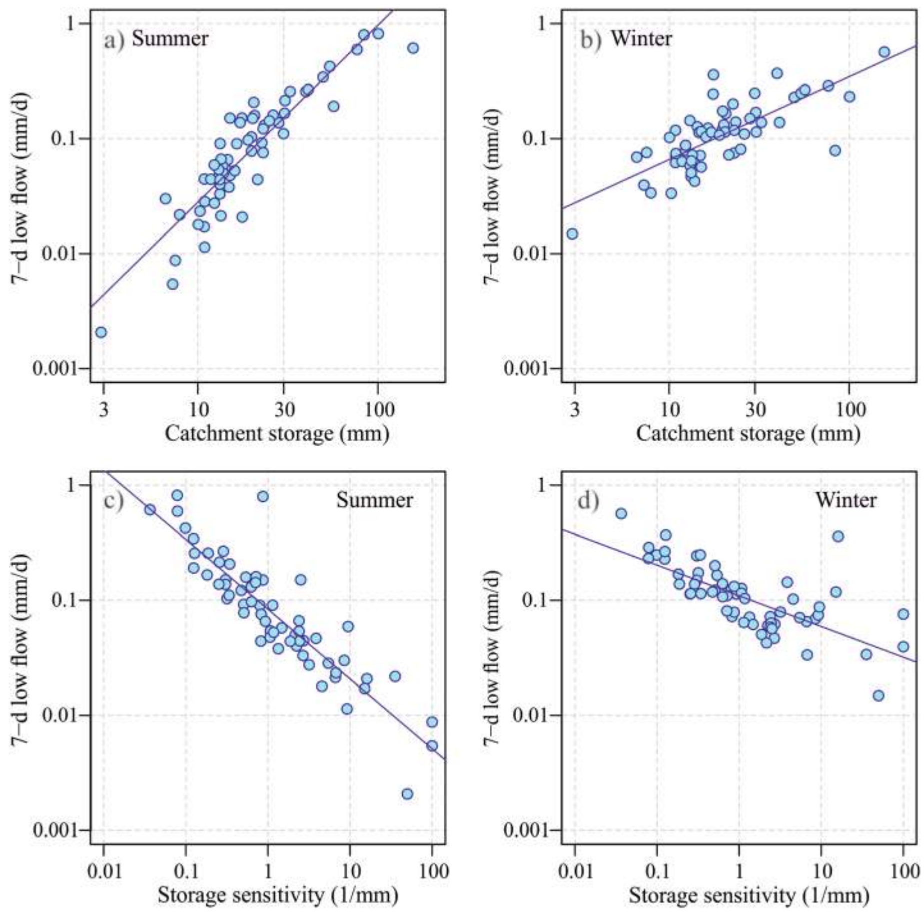

Figure 2. Catchment storage (S_C) and 7-day low flow in (a) summer and (b) winter. Storage sensitivity (ε_S) and 7-day low flow in (c) summer and (d) winter.

3.3. Climate Controls on Catchment Storage Properties and Low Flows

PC1, representing the climate, was used as the predictor variable for the GAM analyses of catchment storage and storage sensitivity of streamflow and low flows (Figures 3a–3d). Storage sensitivity showed a clear negative association with PC1, whereas for catchment storage and summer low flows the association was positive. For winter low flows, the relationship was less clear. Color coding (Figure 3) revealed that catchments covered by agriculture and clay/silt soils are located in areas with less snow and warmer temperatures, as suggested by the PC1 loadings. The size of the partial residuals in Figure 3 shows the amount of sand/gravel soils in the study catchments. One catchment with the highest percentage of sand/gravel soils was an outlier, especially in the low flow graphs (Figures 3c and 3d). The shape of the response curves for GAMs created in LOOCV analysis showed no significant changes and stayed inside the 2× standard error confidence bands of the main GAMs, with only moderate changes in explained deviance and p values (Figures 3a–3d).

The association between climate/snow and 7-day low flow was investigated in more detail using S/P ratio, as snowmelt was expected to affect low flows, especially in areas with more snow in the north and east of Finland. Moreover, the S/P ratio was assumed to be a more accurate measure of snow than other snow parameters, because it was derived from the longest and most consistent data set on precipitation and temperature. We identified a threshold at which the association between precipitation falling as snow (S/P ratio) and summer low flow began to strengthen (Figure 4). The relationship between S/P ratio and summer 7-day low flow in the GAM was strong (60% of deviance explained, $p < 0.001$) and generally positive for the whole range of S/P ratio values. However, when the S/P ratio was above 0.35, summer 7-day low flow started to increase rapidly. At an S/P ratio of between 0.3 and 0.35 the impact was negligible on average, while at

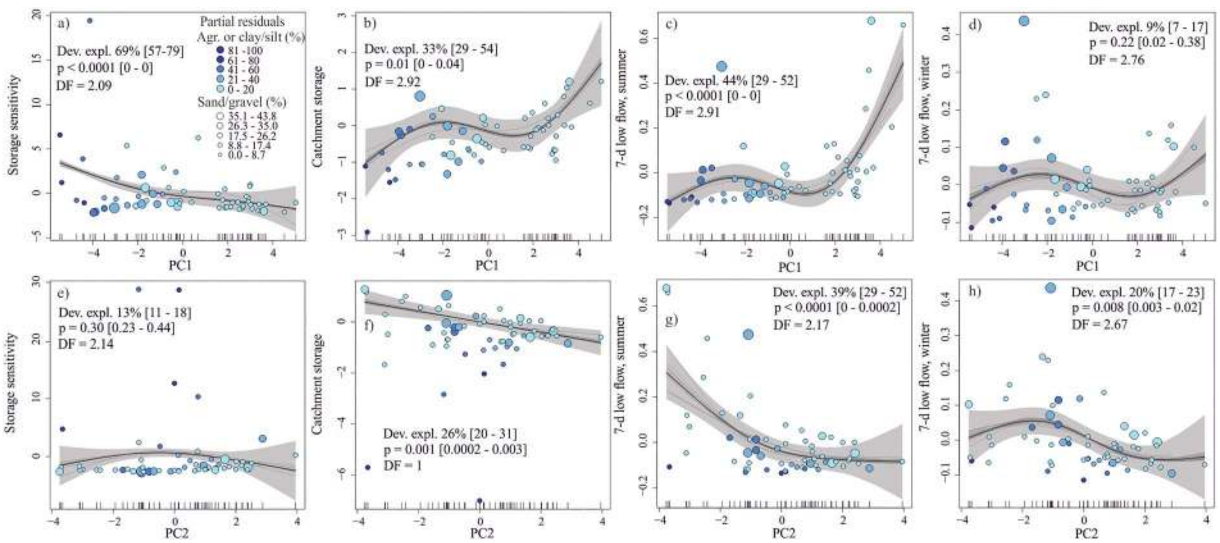

Figure 3. Generalized additive model-based response curves (black) for PC scores (a–d for PC1 and e–h for PC2) and (a, e) storage sensitivity (ε_S), (b, f) catchment storage (S_C), (c, g) 7-day summer low flow, and (d, h) 7-day winter low flow. Higher values for PC1 reflect mainly more snow influence, lower temperatures, and higher mean elevation, whereas lower values reflect higher percentage of clay/silt soils and agriculture. Higher values for PC2 reflect mainly drained and forested peatlands, whereas lower values reflect higher mean slope of the catchment. Explained deviance (Dev. expl.; %), p value, and degrees of freedom (DF) of the model are shown in each diagram, with ranges for explained deviance and p values from leave-one-out cross validation in brackets. Response curves from leave-one-out cross validation are shown in dark gray. Standardized partial residuals (unitless, shown on the y axis) are the estimates of the response variable using only the smooth term plus the residuals from the full model. Color coding for the partial residuals shows the percentage of agriculture and clay/silt soils, while size coding shows the percentage of sand/gravel soils. Shaded area shows the confidence interval of 2 standard errors for the smooth term, including the uncertainty of overall mean. Tick marks on the x axis indicate the location of the data points. PC = principal component.

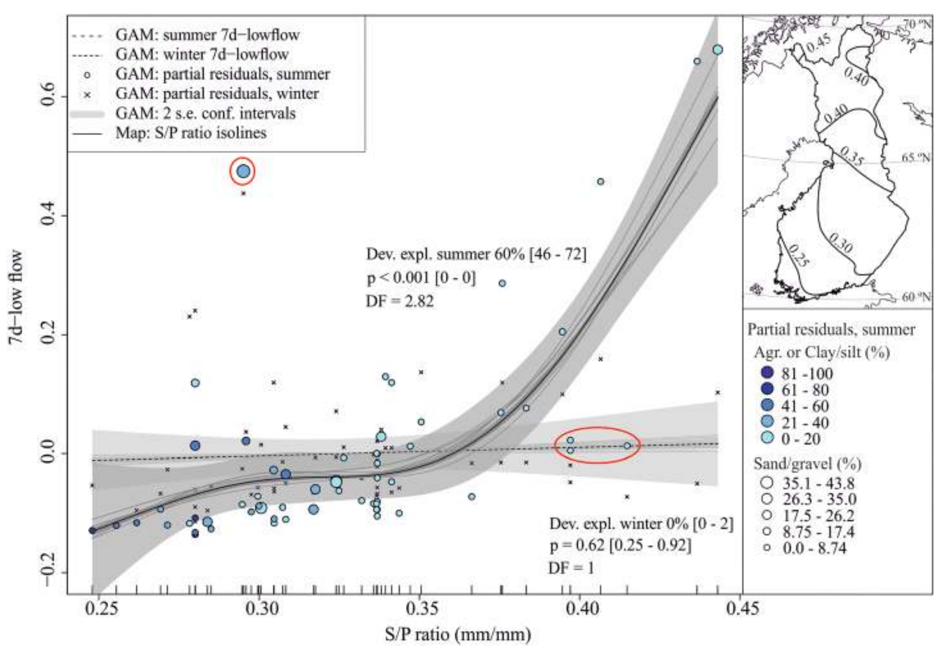

Figure 4. Generalized additive models (GAMs) of 7-day low flow (mm/day) in summer and winter explained by snow to total precipitation ratio (S/P, mm/mm). The relationship between 7-day *summer* low flow and S/P ratio is strong ($p < 0.001$, 60% of deviance explained), whereas the relationship with 7-day *winter* low flow is not significant ($p > 0.6$, 0.4% of deviance explained). Ranges for explained deviance and p values from leave-one-out cross validation in brackets after the values from main model. Response curves from leave-one-out cross validation are shown in dark gray. Standardized partial residuals (unitless) are shown on the y axis. Color coding for the partial residuals shows the percentage of agriculture and clay/silt soils, while size coding shows the percentage of sand/gravel soils. Outliers (shown inside red circles) at S/P ratio around 0.40 are catchments with a high percentage of drained peatland, while the outlier at S/P ratio 0.29 is a catchment with a large sand/gravel deposit. Shaded area shows the confidence interval of 2 standard errors, including the uncertainty of overall mean. Tick marks on the x axis indicate the location of the data points. Gaussian family with identity link function was used, and at most 3 degrees of freedom were allowed in GAM ($n = 61$). The insert shows a map of the study area with S/P isolines.

Table 1
Summary of PCA of Climate and Catchment Characteristics

Characteristics	PC1	PC2
Eigenvalue	8.0	3.2
Percentage explained	41.1	16.6
Cumulative percentage explained	41.1	58.7
Mean elevation (MASL)	**0.29**	−0.16
Mean slope (degrees)	−0.04	**−0.44**
Sand/gravel (%)	−0.11	0.00
Clay/silt (%)	**−0.26**	−0.09
Till (%)	0.21	−0.01
Drained peatland (%)	0.09	**0.43**
Pristine peatland (%)	**0.22**	0.15
Peatland total (%)	0.21	**0.41**
Agriculture (%)	**−0.26**	0.01
Forest on mineral (%)	0.06	**−0.28**
Forest on peat (%)	0.16	**0.44**
Lakes (%)	0.09	0.04
DoY for max SWE	**0.33**	−0.08
DoY for snow end	**0.32**	−0.12
Climate elasticity (mm/mm)	−0.04	0.15
Air temperature (°C)	**−0.32**	0.09
Max SWE (mm)	**0.33**	−0.02
S/P ratio (mm/mm)	**0.31**	−0.14
P/PET (mm/mm)	0.25	−0.23

Note. The highest loadings for the first and second principal component (PC1 and PC2) are shown in bold. See supporting information Figure S5 for PCA biplot of climate and catchment characteristics and catchments. PCA = principal component analysis; MASL = m above sea level; DoY = day of year; SWE = snow water equivalent; S/P ratio = snow to precipitation ratio; PET = precipitation/potential evaporation (wetness index).

values below 0.3 summer low flow started to decrease, reflecting a greater area of agriculture and clay/silt soils (Figure 4, color coded). There was a clear outlier at an S/P ratio of 0.29 (Figure 4). The catchment in question had the highest percentage of gravel/sand soils, typical of productive aquifers in the region (Kløve et al., 2012), sustaining substantial baseflow in the catchment. Three outliers at an S/P ratio of 0.39 and 0.41 were catchments that contain heavily drained peatlands (approximately one third of catchment area) used for forestry and peat extraction. Interestingly, the data showed no association between winter 7-day low flow and S/P ratio. The results did not show high sensitivity in LOOCV, as indicated by the response curve shapes, percentage of deviance explained, and *p* values (Figure 4).

3.4. Catchment Characteristics Controlling Storage Properties and Low Flows

PC2, representing the catchment characteristics (excluding agriculture, clay/silt soils, pristine peatlands, and mean elevation, which were incorporated in PC1), was used as the predictor variable in GAM analysis for storage indices and low flows. High values of PC2 represented catchments with more drained/forested peatlands and lower mean slope, whereas low values indicated higher proportion of forest on mineral soil. Strong negative associations were found between PC2 and catchment storage and winter and summer low flows, with minor sensitivity in LOOCV (Figures 3e–3h). No association was found between PC2 and storage sensitivity. Color coding of the partial residuals revealed that catchments with more clay/silt/agriculture had higher storage sensitivity and smaller storage volume (dark blue outliers in Figures 3e and 3f). Without those outliers, the partial residuals indicated a slight positive relationship between PC2 and storage sensitivity above a PC2 value of zero (Figure 3e). Size coding (Figures 3g and 3h) showed that the catchment with the highest sand/gravel soil cover was again a clear positive outlier in low flow graphs.

More detailed investigation of peatland drainage operations and low flows showed a strong negative association between drained peatland percentage and summer (Figure 5) and winter 7-day low flows (supporting information Figure S6). When the minimum peatland percentage increased from 0% to 25% and 40%, the percentage of deviance explained for summer low flow increased from 8% to 24% and 27%, respectively. For pristine peatlands, the associations were less clear, although some relationship patterns between low flows and pristine peatland cover were observed. LOOCV did not reveal any major sensitivity in the main results.

The SAC in the residuals in GAMs (supporting information Figures S7–S9) was mainly low and statistically nonsignificant. Statistically significant SAC was found in a few cases, probably because some catchments were clustered close to each other, which can have a slight impact on the models. However, for the main results, the potential influence of residual SAC was considered to be low.

4. Discussion

4.1. Spatiotemporal Variation in Catchment Storage Properties

We observed notable spatial variability in catchment storage and sensitivity, which could largely be explained by climate conditions, catchment characteristics, and their interconnections. This is in agreement with previous findings suggesting that the natural hydrological response of a catchment is a result of long-term interactions between climate, geology, and vegetation, later modified by anthropogenic effects (Blöschl et al., 2013). In the 61 Finnish catchments examined in the present study, coastal areas at low elevation with younger soils and lower snow to precipitation (S/P) ratio (higher temperature) showed lower catchment storage and higher sensitivity of streamflow (Figure 1). This indicates vulnerability of these areas to climate variability and future changes in climate and land use. In contrast, forested northern and eastern

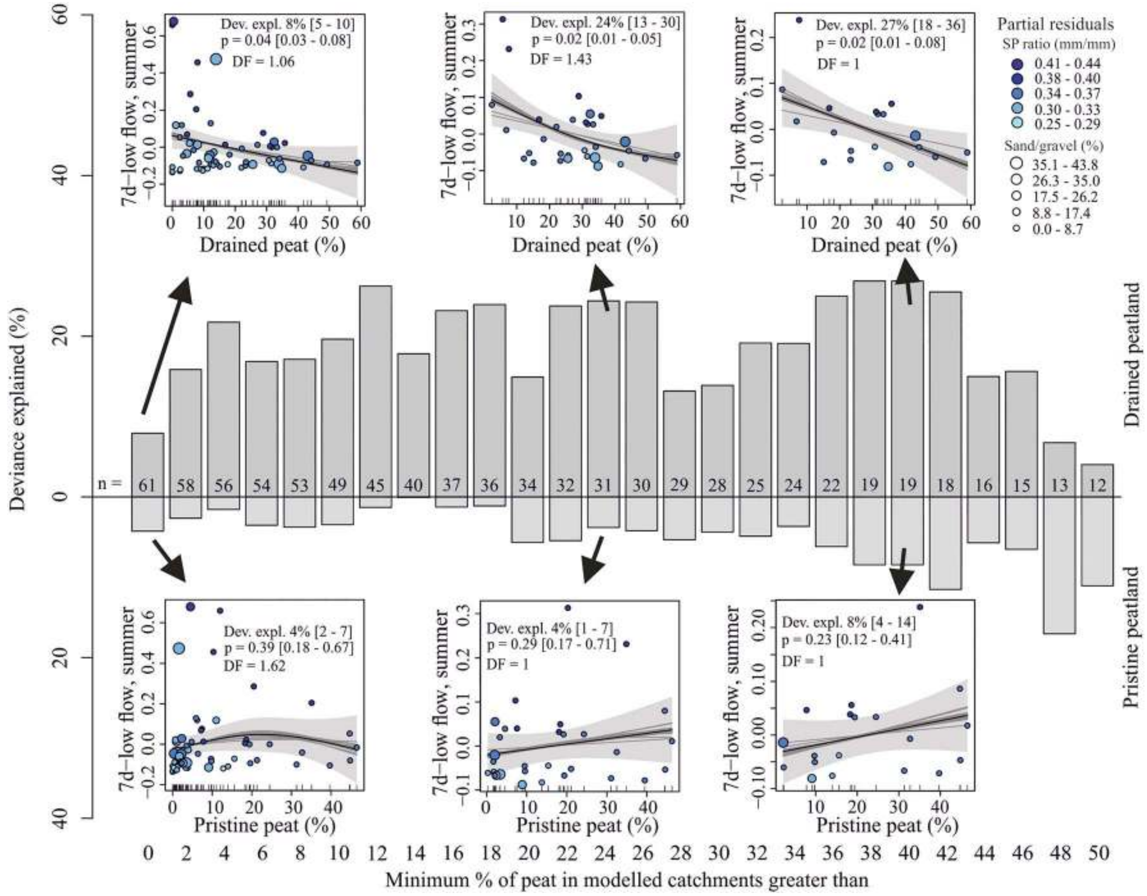

Figure 5. Deviance explained in generalized additive models of 7-day summer low flow explained by area (%) of pristine (light gray bars) and drained (dark gray bars) peatlands over total catchment area. Minimum amount of total peatland (%) in the catchments included in the model is shown on the *x* axis. Values inside the upper bars show the number of observations (*n*) in each model. Example plots above and below bars are shown for models where all catchments are included, catchments where total peat area exceeds 25%, and catchments where total peat area exceeds 40%. Standardized partial residuals (unitless) are shown on the *y* axis of the example plots. Color coding for the partial residuals shows the S/P ratio, while size coding shows the percentage of sand/gravel soils. Ranges for explained deviance and *p* values from leave-one-out cross validation are shown in brackets after the values from main model. Response curves from leave-one-out cross validation are shown in dark gray. Shaded area shows the confidence interval of 2 standard errors, including the uncertainty of overall mean. Tick marks on the *x* axis of the example plots indicate the location of the data points. Gaussian family with identity link function was used, and at most 3 degrees of freedom were allowed in generalized additive models.

areas with glacial till and peat soils generally showed higher storage and lower storage sensitivity of streamflow under current conditions.

Seven-day low flow during both summer and winter was strongly related to catchment storage (Figure 2, note logarithmic scale), which confirms previous findings of a nonlinear connection between catchment storage and ecologically and socioeconomically important low flows (Eltahir & Yeh, 1999). A similar relationship was found between 7-day low flows and storage sensitivity of streamflow, which confirms the suitability of streamflow sensitivity as a measure of catchment vulnerability (Berghuijs et al., 2016). Such relationships were expected in the present study, because the storage indices were derived using daily discharge data and the dependency between Q_{85} and max_{BF} (see supporting information Table S1), which we used in calculations of storage properties and low flow. The strong link between storage properties and 7-day summer low flow can be explained by high evapotranspiration during summer, especially in the south, causing faster drainage of the storage, and the smaller amount and earlier timing of spring snowmelt in southern areas (Godsey et al., 2014). In contrast, evapotranspiration is lower in the north and snowmelt water can sustain the low flows in spring and early summer. The weaker relationship between storage indices and winter low flow can be a result of decreased evapotranspiration during the rainy autumn season, enabling recharge and sequential release of water during winter. Additionally, in northern areas precipitation falls mostly as snow, preventing groundwater recharge and consequently increased winter low flow, while in the south there are more winter rain events, preventing catchment storage depletion.

4.2. Climate Controls on Catchment Storage Properties and Low Flow

We found support for hypothesis H_1, as snow and climate factors, represented by PC1, showed a strong association with catchment storage properties (Figures 3a and 3b). This agrees with previous suggestions that climate is the first-order control on hydrology (Devito et al., 2005). PC1 was negatively loaded with air temperature, suggesting decreased storage and increased sensitivity in warmer regions. However, the impact can be expected to propagate through its relationship with snow properties (with high loads for PC1) and evapotranspiration (with moderate load for PC1 through wetness index). Furthermore, the loadings for PC1 showed covariation with certain catchment characteristics, suggesting an increase in their role in hydrology relative to climate, as discussed further in section 4.3 of this paper. Climate and snow were also found to have a strong association with 7-day summer low flow (Figure 3c), providing important information about the relationship between climate and streamflow. Indeed, higher low flows not only support stream ecosystems directly (Poff et al., 1997) but also create thermal buffer capacity in streams and decrease the influence of atmospheric energy exchanges on stream temperatures, especially in headwaters (Orr et al., 2015; Sinokrot & Gulliver, 2000).

Our results showed a strong association between S/P ratio and summer low flows, as also shown in recent studies (Godsey et al., 2014; Jenicek et al., 2016). As expected, the S/P ratio, which is strongly dependent on air temperature, generally dominated the observed storage behavior in northern boreal headwater catchments. S/P ratio was observed to be correlated strongly with other climate and land cover variables (supporting information Figure S2; PC1 in Table 1), which impeded the identification of hydrological controls. However, based on recent studies (Godsey et al., 2014; Jenicek et al., 2016) and process knowledge, the results can be considered logical, because the high SWE and late snowmelt in the northern boreal region potentially fill the soil storage and recharge the groundwater storage, supporting low flows also during summer months when the evapotranspiration demand is high.

Interestingly, we found a distinct threshold for S/P in supporting summer low flows, with S/P ratio values lower than 0.35 resulting in a flattening relationship between S/P ratio and 7-day summer low flow (Figure 4). This strongly suggests that the climate, especially snow, dominates hydrological storage processes above this S/P threshold; that is, there is enough snowmelt recharge and lower evapotranspiration, which enables the catchment to sustain higher summer low flows. Below the 0.35 S/P threshold, temperature, rainfall, and physiographical properties of catchments exert more direct control on the flow regime. Catchments at the S/P threshold zone can be considered especially sensitive to changes in snow cover, because in a warming climate the decreased snow storage will reduce the buffer for climate variability, as the geographical location of the S/P threshold zone is moving northeast in Fennoscandia. Similar transition areas can be found in many boreal and Arctic regions, especially in coastal areas, which are reported to be most sensitive to changes in hydrology resulting from climate change (Prowse et al., 2015). Moreover, a shift in the S/P ratio threshold can increase the mismatch between supply and demand for water resources in a larger proportion of the boreal zone, which can have significant implications for ecology (Mustonen et al., 2018; Vörösmarty et al., 2010) and water security (Berghuijs et al., 2014). Our results also revealed another, less prominent, threshold at an S/P ratio of 0.3, below which summer low flows are already sensitive to climate perturbations. However, the driver there appears to be catchment characteristics together with climate, as agricultural areas and clay/silt soils are more abundant in the catchments concerned, as shown by the color coding in Figure 4.

4.3. Catchment Characteristic Controls on Catchment Storage Properties and Low Flow

The GAM analysis for PC1 showed that catchments with the smallest storage and highest storage sensitivity are located at lower elevations (Table 1 and Figures 3a and 3b). Postglacial clay/silt sea sediments extending up to 100–200 km inland affect the soil, land use, and vegetation properties in these areas. Consequently, agricultural areas often coexist with fertile alluvial low permeability clay/silt soils (both loaded in PC1), decreasing the water storage by land drainage and increasing water demand. These findings suggest that, while climate remains the primary control on hydrology in these lowland areas, catchment characteristics have relatively higher influence than in the snow-dominated regions. The catchments with the greatest storage and the lowest storage sensitivity were shown to be located at higher elevations in the north and interior of Finland, where basal till dominates the catchment surface geology and peatland is more abundant (Figures 1, 3a, and 3b). The loadings from till soils and pristine peatlands in PC1 were positive and moderate (Table 1), suggesting their interaction with climate in supporting storage and summer low flows. The results for till agree with previous findings for boreal Canada, where moderate depth of basal till has been observed to maintain low flow, resulting in fewer days of zero flow (Buttle & Eimers, 2009; Devito et al., 1996). For peatlands, this indicates that the data support our hypothesis H_2 that pristine peatlands can buffer the influence of changes in climate on streamflow, as there are several feedbacks in peatland systems for moderating stresses (Waddington et al., 2015). This can be associated with increased groundwater outflow from the catchment, as peatlands are often located in groundwater discharge areas (Winter & Woo, 1990).

However, for drained and forested peatlands (loaded in PC2), the results suggest a decrease in catchment storage and in both summer and winter low flows (Figures 3f–3h). PC2 was also loaded strongly (negatively) by mean slope, which suggests that catchment storage and low flows are greater in catchments with more variable topography and that drained peatlands are usually found on relatively flat terrain. Forest on mineral soil was moderately (negatively) loaded in PC2, indicating that it increases storage properties and low flows at catchment scale, supporting findings in a recent study by Karlsen et al. (2016).

Further analysis of the impact of peatlands to test our hypothesis H_2 showed, for the first time for a large data set of boreal catchments, that peatland drainage is indeed associated with decreased low flows at catchment scale during winter and summer. This association was stronger when catchments with no peatland were omitted from the analysis and a progressively increasing threshold for relative proportion of peatland in catchments was introduced (Figure 5 and supporting information Figure S6). Interestingly, our data did not show strong relationships between low flows and percentage of pristine peatlands, as also reported elsewhere (Winter & Woo, 1990), suggesting that wetlands do not generally regulate seasonal streamflow. This contradicts our hypothesis H_2, the opposing indications from GAM results for PC1, and recent findings that peatlands are the primary source of runoff during dry periods (Gracz et al., 2015). This discrepancy can be a result of low representation of pristine peatlands (max. 46.5%, median 4.5% of catchment area) in our data set or of coexistence of pristine and drained peatlands in many catchments. Bog- and fen-dominated peatland areas can also have different connectivity and storage properties, which are further affected by catchment topography and geology (Quinton et al., 2003). However, there was insufficient information in our data set to make a distinction between peatland types.

5. Conclusions

With a warming climate, snow conditions are changing rapidly, with severe impacts on hydrological conditions in boreal regions. In this study, we detected some geographical variation in the resilience and sensitivity of boreal catchments. Substitution of space for time has been used elsewhere to draw inferences about catchment-scale responses to climate change (e.g., Singh et al., 2011). If this approach is valid for the Finnish catchments, then our findings suggest that, in a warming climate, the changes in hydrological processes related to snow conditions will be pronounced at a certain S/P ratio threshold, highlighting the strong connectivity between snow and ecologically important summer low flows. Pristine peatlands were indicated to support low flows, but the results were inconclusive and further analysis with larger data sets is required. Existing evidence on the impact of drained peatlands on low flows is also inconclusive, but we found that peatland drainage decreased catchment storage and low flows during both summer and winter. This indicates that peatland restoration could improve hydroecological conditions at catchment scale, which is important information for policymakers. The results of this study can be used to mitigate impacts of climate change and to guide land use management in other similar boreal and high-latitude regions where rapid climate change is projected.

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