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# Controls on root zone storage capacity in boreal regions

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**Abstract.** The root zone storage capacity ($S_r$) of the vegetation is an important parameter for the hydrological behaviour of a catchment. Often this $S_r$ is derived from soil and vegetation data, but a new method uses climate data to estimate $S_r$ under the assumption that vegetation adapts its root zone capacity to overcome dry periods. This method also enables to account for the temporal variability of $S_r$ in case of changing climate or land cover. This study applies the new method in 64 catchments in Finland to investigate the controls on $S_r$ in boreal regions. The relations were assessed between climate derived $S_r$-values and detailed vegetation characteristics (leaf cover, tree length, root biomass), climate variables (precipitation-potential evaporation rate, mean annual temperature, max snow water equivalent, snow-off date) and land cover types. The results show that especially the phase difference between snow-off date and onset of potential evaporation has a large influence on the derived $S_r$; results even indicate that (non-)coincidence of snow melt and potential evaporation can cause a division between catchments with a high and a low $S_r$-value. From this study, it can be concluded that the climate derived root zone storage capacity leads to plausible results in boreal areas and that besides from climate variables, catchment vegetation characteristics can also be directly linked to the derived $S_r$-values. As the climate derived $S_r$ enables incorporating climatic and vegetation conditions in a hydrological parameter, it could be beneficial to assess the effects of changing climate and environmental conditions in boreal regions.

## 1 Introduction

The hydrological cycle of boreal regions is changing vastly as a result of climate change (Prowse et al., 2015) and increasing anthropogenic land use activities (Instanes et al., 2016). Retreating seasonal snow cover, increasing temperatures and precipitation, and shifts in precipitation from snow to rainfall are a few examples of alterations of the boreal hydrological cycle (Bring et al., 2016). Consequences of warming are likely to be most severe in boreal systems, as slight changes in temperature can alter magnitude and timing of snow accumulation and melt (Carey et al., 2010). Predicted changes create climatic conditions at certain higher latitudes, which are similar to those at lower latitudes a few decades earlier (Intergovernmental Panel on Climate Change, 2014). These changes in climate will have an effect on different vegetation types while at the same time, land use activities have been intensified especially in European countries and are predicted to increase in near future due to a "green shift" to a bio-based economy (Golembiewski et al., 2015). The occurring land use changes consist of modifications in actual

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land use (increase in forest cover), but also of more intensive use of forests, including clear cutting, forest trimming, residual harvest and of increasing utilisation of peatland forests as source for biomass.

Especially under these changing conditions, a proper hydrological understanding of boreal catchments is needed (Waddington et al., 2015; Laudon et al., 2017) to understand the sensitivity and resilience of catchments (Tetzlaff et al., 2013), but also to assess the effect of possible measures. Many studies have been conducted to explore hydrological changes resulting from land use activities (Ide et al., 2013; Mannerkoski et al., 2005; Nieminen et al., 2017), but so far none have studied changes in transpiration (patterns) at the catchment scale in boreal regions. The partitioning between transpiration and runoff is largely determined by the root zone storage capacity ($S_r$) of the vegetation (e.g., Zhang et al., 2001), thus detailed knowledge about this parameter can increase the hydrological understanding of catchments under different conditions.

Traditionally, $S_r$ is estimated from soil and vegetation data or calibrated in a hydrological model. Following the analysis that $S_r$ is strongly related to climate variables (e.g., Kleidon and Heimann, 1998; Gentine et al., 2012; Gimbel et al., 2016), Gao et al. (2014) developed a new method to estimate $S_r$ from climate data. Subsequently, several studies have been carried out in which this method was used. For example, Wang-Erlandsson et al. (2016) used earth observation data to estimate $S_r$ globally; de Boer-Euser et al. (2016) did a comparison between the influence of soil and climate on $S_r$; Nijzink et al. (2016) investigated the change in $S_r$ after deforestation and Zhao et al. (2016) introduced a snow component to the method and carried out a sensitivity analysis.

Thus, climate (or the balance between precipitation and transpiration) has a large influence on the developed $S_r$. However, it is very likely that root development is affected by other factors, including nutrients (e.g., Shahzad and Amtmann, 2017), the survival mechanism of the vegetation (e.g., Christina et al., 2017), or reduced space for root development due to shallow soil layer or high ground water tables (e.g., Soylu et al., 2014). $S_r$ is expected to change if any of these factors changes, which has consequences for the hydrology of the area (e.g., Saft et al., 2015). Assessing the (future) hydrology of boreal catch could benefit from a better understanding of the relation between $S_r$ and (changing) climatic and vegetation conditions.

At this moment, a climate derived root zone storage capacity has not yet been specifically tested for boreal areas. Applying the method in these areas requires adding a snow component to the method. Earlier studies showed that climate has a strong influence on $S_r$, but other controls have not yet been studied in combination with a climate derived $S_r$. Therefore, this paper assesses the relation between the root zone storage capacity and vegetation and climate variables, in order to better understand what mainly controls the root zone storage capacity in boreal regions. The aim of the study is to determine $S_r$ values for different boreal catchments and expectations are to find variation resulting from climate conditions, vegetation type and proportion of peatlands. Furthermore, it is expected that the influence of anthropogenic activities can be seen, especially with respect to intensive use and drainage of peatlands.

## 2 Methods

### 2.1 Characteristics study catchments

A total of 64 headwater catchments were used, spread over Finland. The catchments are located in different boreal regions (south, mid- and north boreal; Ahti et al., 1968) and thus have different climate conditions and vegetation patterns (Figure 1). All sites belong to National network of small catchments (Seuna and Linjama, 2004) and have been used in various studies (e.g., Kortelainen et al., 2006; Sarkkola et al., 2012, 2013b). The catchments used in this study were selected based on the availability of long-term runoff records, snow line records and meteorological data from the catchments.

The climate of the region is humid, with annual average air temperatures varying from 5 °C in the south to -2 °C in the north and average precipitation of 600-700 mm/y in the south and 450-550 mm/y in the north. Average maximum snow depth by the end of March is 50-400 mm in the south and 600-800 mm in the north.

The principal land cover in the study catchments is forest (with a median of 81% coverage of evergreen, deciduous and mixed forest), followed by shrubs and herbaceous vegetation, inland waters and wetlands. Agricultural activities were present in some of the southern sites. The surface area of the catchments ranges from 0.07 $km^2$ to 122 $km^2$ (median 6.15 $km^2$).

The soil type in the southern sites is dominated by clay layers whereas basal till and peatland cover is increasing when moving towards east and north. The catchments have relatively flat topography with a mean difference in elevation of approximately 70 m. The selected catchments do not contain any urban settlements.

Tables 1 and 2 in the supplementary material give an overview of available vegetation and climate characteristics of the study catchments.

### 2.2 Data use and correction

Two sets of data were used in the study: one for the calculation of the climate derived root zone storage capacity and one to investigate the different controls on $S_r$. For the $S_r$ calculations precipitation, snow water equivalent, potential evaporation and discharge data were used. For investigating different controls, additional data were used about leaf cover, tree length, root biomass, temperature, snow off date and land cover.

Daily discharge was measured with water stage recorders and weirs were routinely checked for errors by the Finnish Environment Institute. Precipitation ($P$) and temperature data were taken from the national 10 km x 10 km interpolated grid produced by Finnish Meteorological Institute (FMI) (Paituli database[1]). The snow line data for snow water equivalent ($S_{SWE}$), potential evaporation ($E_p$) using pan measurements and runoff data used were obtained from Finnish Environmental Institute's open database (Hertta). The snow line measurement points used in the study were either located inside or in close proximity of the study catchments.

Corine Land Cover 2012 data (Paituli database) was used for determining the land cover of the study catchments. The surface lithology and geology data are based on the Surface Geology Map of Finland (Hakku database[2]). The national forest inventory

[1] https://avaa.tdata.fi/web/paituli/latauspalvelu
[2] https://hakku.gtk.fi/en/locations/search

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database (LUKE open data[3]) was used to calculate root biomass, tree length and leaf cover of the sites. Tree data was available for Pine, Spruce and Deciduous forest types. Drained and pristine peatlands masks were obtained from Finnish Environmental Institute (SYKE).

Although the snow line measurement points were either located inside or in close proximity of the study catchments, for some catchments the increase in $S_{SWE}$ during a season was higher than the total measured precipitation for the same period. As the precipitation data was assumed to be more reliable and less spatially variable, the $S_{SWE}$ data was adjusted on a daily basis to make it consistent with the precipitation data.

### 2.3 Climate derived root zone storage capacity

To test the controls on root zone storage capacity, a climate derived root zone storage capacity ($S_r$) was used. The derivation of this $S_r$ is based on the principle that vegetation will create a buffer with its root system just sufficient to overcome a drought with a certain return period. Investing less in a root system would lead to the vegetation dying in case of drought and investing more is not efficient in terms of carbon use. For the calculation of $S_r$ the daily balance between infiltration and transpiration is used to simulate the amount of storage the vegetation would need to cover the infiltration deficit. In this study the same base calculation was used as in de Boer-Euser et al. (2016), but as snow accumulation cannot be neglected in Finland, an additional snow module was added (Figure 2). Due to the high forest cover, for all analyses a $S_r$ was used corresponding to a drought with a return period of 20 years.

In the original $S_r$ calculations (e.g., Gao et al., 2014; de Boer-Euser et al., 2016) it is assumed that a part of the precipitation is intercepted and the remaining infiltrates immediately, unless the soil moisture deficit is zero. However, in case of solid precipitation, the precipitation is stored on the soil surface for days to months and only infiltrates during the snow melt period. As this is a relevant process in most of study catchments, a snow component (Equations 1-4) was added to the calculation method used by de Boer-Euser et al. (2016). The change in $S_{SWE}$ was used to determine the amount of precipitation stored on and infiltrating into the soil daily. Interception was only taken into account in case of liquid precipitation and an interception threshold of 1.5 mm was assumed for all catchments. Sublimation was not taken into account, as potential evaporation is generally (very) low when snow cover is present.

For estimating $S_r$, data from 1 January 1990 to 31 December 2012 were used. For precipitation and snow water equivalent daily values were used, while for discharge and potential evaporation data, long term yearly and monthly average were used respectively. For some of the catchments discharge data was limitedly available for the study period; for these catchments older discharge data was taken into account as well to obtain a long term average.

$$P_{rz} = P_i + P_m \tag{1}$$

[3]http://kartta.metla.fi/opendata/valinta.html

$$P_i = \begin{cases} 0, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} < 0 \\ 1, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} > 0 \\ P_t, & \text{if } S_{SWE} = 0 \end{cases} \tag{2}$$

$$P_m = \begin{cases} P_t - \Delta S_{SWE}, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} < 0 \\ 0, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} > 0 \\ 0, & \text{if } S_{SWE} = 0 \end{cases} \tag{3}$$

$$\Delta S_{SWE} = S_{SWE,t=i} - S_{SWE,t=i-1} \tag{4}$$

with, $P_{rz}$ = infiltration, $P_t$ total precipitation, $P_i$ effective precipitation, $P_m$ snow melt, $S_{SWE}$ snow water equivalent.

### 2.4 Assumptions for estimating root zone storage capacity

The calculation of the climate derived root zone storage capacity involves sevaral assumptions, as also discussed by de Boer-Euser et al. (2016) and Wang-Erlandsson et al. (2016). The data available for the study catchments can be used to explore the relations between $S_r$ and other vegetation properties and thus the plausibility of two of these assumptions.

First, an essential part of the $S_r$ calculation is the estimation of the transpiration demand. The average transpiration for the calculations is derived from the water balance (difference between precipitation and discharge), and is reflected in the derived $S_r$-values. As the precipitation is relatively similar for the study catchments (mean of 1.65 mm/d, with a standard deviation of 0.14 mm/d), higher transpiration demands will lead to higher $S_r$-values. Similarly, higher transpiration demands indicate that the vegetation can use more (solar) energy for their development and thus, establishing more above ground biomass as well. So, it is expected that the derived $S_r$ values are related to vegetation properties like leaf cover and tree length.

Second, the climate derived $S_r$ is a conceptual parameter and is expected to represent a representative storage capacity in a catchment. In that sense it cannot be directly measured in the field; despite this, it is expected that vegetation actually has to increase its root biomass in order to increase the root zone storage capacity. Therefore, the derived $S_r$ is compared with data about root biomass for three different tree types.

### 2.5 Controls on root zone storage capacity

In addition to these assumptions, also the relation between the derived root zone storage and a set of catchment characteristics was investigated. It is expected that these relations can be informative for the variables that control the development of the root zone storage capacity.

First, the relation with climate was investigated; the method used to derive $S_r$ is based on climate data, so it is expected that climate has a strong control on the derived $S_r$ values. However, by comparing the spatial patterns of climate variables and derived $S_r$-values and their mutual correlation, it can be analysed which climate variables have the strongest influence on $S_r$. Second, the relation of $S_r$ with land cover and vegetation type was investigated. Different vegetation types occur in different climates and ecosystems and can have different survival mechanisms. Therefore, the vegetation types and their transpiration needs can have a strong control on the derived $S_r$. The vegetation types included in the analysis are forest, pristine peatlands, drained peatlands and agricultural area.

The relations between the estimated $S_r$-values and catchment characteristics were assessed in two ways. First, scatterplots between $S_r$ and the various characteristics were analysed; second, correlation statistics were calculated. To assess the correlation between the different variables, the non-parametric Spearman's correlation coefficient was used. For analysis of the threshold behaviour in $S_r$ (presented in Section 3.3), the catchments were divided into two groups separated by a $S_r$ of 115 mm. For both groups the significant differences between catchment characteristics were investigated.

## 3 Results

### 3.1 Assumptions for estimating root zone storage capacity

Estimated root zone storage capacities were compared with vegetation characteristics in the study catchments. Figure 3 shows the relation between $S_r$ and average leaf cover (top row) and tree length (bottom row). For both comparisons a distinction is made between different land cover (forest, peatlands, agriculture) and the boreal regions. Some correlation can be observed between $S_r$ and leaf cover for the catchments with forest (a) and peatland (b) cover (see Figure 8 for significant correlations). On the other hand, for catchments with more agricultural cover (c) a wide spread in $S_r$ values can be seen, while the variation in leaf cover is relatively small. The relation between $S_r$ and tree length shows more or less the same pattern: some correlation can be seen for catchments with a high forest cover (e) and this correlation decreases for higher percentages of peatland (f) and agriculture (g). When looking at the different boreal regions (d, h), the correlation between $S_r$ and leaf cover or tree length is mainly present for catchments in the mid-boreal region.

In Figure 4 the relation is shown between the climate derived $S_r$ and the observed root biomass in the catchments. A distinction is made between three tree types: pine, spruce and deciduous trees. Root biomass of spruce and deciduous trees mainly has a positive correlation with $S_r$, with an increasing spread in the data for the more southern catchments. One exemption is the root biomass of spruce in the mid-boreal region; here no clear correlation with $S_r$ can be observed. The correlation between $S_r$ and root biomass of pine is very interesting: the northern region shows a slight positive correlation, but for the middle and southern region a negative correlation is shown. Figure 4d combines the results for all tree types and shows indeed a mixture of the results observed for the individual tree types. In general, a positive correlation exists between $S_r$ and root biomass, which seems to weaken for catchments in the south boreal region, where $S_r$ values are higher.

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### 3.2 Controls on root zone storage capacity

Two types of controls on root zone storage capacity were investigated: the influence of different climate variables and the influence of land cover. The first one can be split into the precipitation and evaporation on one hand and snow cover and melt on the other. Focussing first on the relation between $S_r$ and precipitation and potential evaporation, Figure 5 shows the spatial patterns of $S_r$ and $P/E_p$. $S_r$ values generally decrease from south to north and especially for the mid-boreal region a large difference exists between the eastern and western side of the country. For the catchments in the north and mid-boreal regions larger $S_r$-values generally coincide with smaller $P/E_p$ ratios, but for the south boreal region this pattern is less clear. The same can be observed from Figure 6a: the catchments in the north and mid-boreal regions show a negative correlation between $S_r$ and $P/E_p$, while in the south boreal region the range in $S_r$ values is large, although the variability in $P/E_p$ is small (see Figure 8 for significant correlations).

The differences in $S_r$ between catchments can partly be explained by mean annual temperature ($T_{AM}$) and snow cover (expressed in snow water equivalent, $S_{SWE}$). Figure 6b shows that $T_{AM}$ clearly distinguishes between boreal regions and that $T_{AM}$ and $S_r$ are positively correlated, which weakens for higher temperatures. Figure 5 further shows that the differences within the mid-boreal region largely coincide with the differences in $S_{SWE}$. A closer look into the correlations between $S_{SWE}$ and $S_r$, shows that a higher maximum $S_{SWE}$ leads to smaller $S_r$ values (Figure 6d). Unsurprisingly, the catchments with a higher maximum $S_{SWE}$ are also the ones with a higher $P/E_p$ ratio (Figure 6a). In addition to this, the snow off date (Figure 6c) is even stronger correlated with $S_r$ than the maximum observed $S_{SWE}$.

Besides climate, also land cover can have an influence on the $S_r$, mainly because different vegetation types have different transpiration patterns and survival strategies. Before analysing correlations between $S_r$ and land cover, it should be noted though that land cover is correlated with climate as well (Figure 1). This is especially relevant for the correlations between $S_r$ and agriculture and forest cover.

Figure 7a shows that with an increase in agricultural area, $S_r$ increases as well. Although the spread in data increases when moving from north to south, the correlation increases for the individual regions as well. Further, a decrease in forested area coincides in general with an increase in $S_r$, but this correlation is not present for the individual regions (Figure 7b). The drained peatlands (Figure 7c) on the other hand show a slight positive correlation with $S_r$ for the north and south boreal regions, while they show a clear negative correlation for the mid-boreal region. While the former three land cover types showed a stronger or weaker gradual relation with $S_r$, the pristine peatlands show strong threshold behaviour. For catchments with more than 20% pristine peatlands, $S_r$ values are below 115 mm. It should be noted though, that catchments with high pristine peatland cover do not occur in the south boreal region.

Figure 8 shows the correlations between $S_r$ and the various catchment characteristics. From this figure it follows that the strongest positive correlation was found between $S_r$ and the mean annual temperature and the strongest negative correlation was found for $S_r$ and the (timing of) maximum $S_{SWE}$. Further, it can be seen that a strong correlation exits between the different vegetation characteristics and between the different climate variables. In addition, the land cover (except for drained peatlands) also shows a strong correlation with the climate variables.

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### 3.3 Threshold behaviour

The results discussed before show to a variable extent a threshold in the relation between the derived $S_r$ and other variables. This threshold is mainly visible in Figures 6 and 7d and seems to be the strongest for snow characteristics (Figure 6c,d) and pristine peatlands (Figure 7d). For all variables the threshold is located at a $S_r$ of approximately 115 mm. To further investigate the origin and position of the threshold the catchments were divided into two groups separated by a $S_r$ of 115 mm. Within the groups statistically significant variations exist in both vegetation, specifically in tree root biomass (pine RBM: Mann-Whitney U-test, p=0.0131; spruce RBM: U-test, p=0.0363) and proportion of peatlands in the catchments (U-test, p=0.0013). At the same time also climatic parameters changed: snow fraction (U-test, p=0.0443), maximum snow water equivalent (max $S_{SWE}$: U-test, p=0.0000), snow-off date (U-test, p=0.0000) and mean annual temperature ($T_{AM}$: U-test, p=0.0000) showed a significant difference between the groups.

As not only the maximum $S_{SWE}$ and $T_{AM}$ are important, but also the snow off date (Figure 6), it is possible that the threshold is related to the phase difference between water input and demand in the catchments. Therefore, Figure 9 shows the period with snow cover and the period in which potential evaporation is above zero for each catchment. In general, for catchments with a $S_r$ smaller than 115 mm (bottom part of the plot), the snow melt and onset of potential evaporation overlap. On the other hand, for catchments with a $S_r$ larger than 115 mm the snow has already melted at the onset of the potential evaporation measurements. In the first case the phase difference between input and demand is decreased, while in the second case it is increased, thus requiring a larger storage capacity. This phase difference explains the origin of the threshold, but not the location at 115mm. A clear reason for the threshold being located at 115 mm could not be found and it might be an artifact of this specific data set.

## 4 Discussion

The presented results show that climate derived root zone capacities are related to vegetation characteristics, climate variables and vegetation cover, which strongly indicates that the $S_r$-method can be used for boreal regions containing seasonal snow cover. According to the results, the correlation between $S_r$ and the tested climate and vegetation variables varies and is not always straight forward. In addition, many of the presented comparisons showed a threshold around a $S_r$-value of 115mm. Possible reasons for this threshold and for differences in correlation are discussed below, together with implications of the findings.

### 4.1 Vegetation characteristics

The derived root zone storage capacities mainly follow the south-north gradient, along which clear vegetation variations occur as well. By using a climate derived root zone storage capacity, it is assumed that the vegetation develops a larger $S_r$ in case it has to deal with higher or more variable transpiration demands. When the transpiration demand in boreal areas is higher, it is likely that vegetation has higher potential to develop as well (ie. more leaf cover, larger trees). Figure 3 shows some correlation

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between $S_r$ and leaf cover or tree length, but this correlation is mainly present below the threshold of 115 mm and hardly present for catchments with more agriculture cover. This seems to indicate that in case of low transpiration demands the plant's resources between below and above soil elements are more equally divided than for areas with higher transpiration demands.

Despite the conceptual character of the climate derived root zone storage capacity, it can be expected that it is positively correlated with root density or root biomass; this study is the first to show this connection for spruce and decideous trees (Figure 4). However, for pine in mid- and south-boreal regions a negative correlation was observed, which means that the vegetation is able to create a larger storage capacity with fewer or thinner roots. This can have multiple reasons, among which, that in these areas the pine trees have other methods to access water, or that the density of pine trees is very low in these catchments, thus their influence on the overall transpiration and storage in the catchments. Interestingly, also the most northern catchment in our data set, with tundra vegetation, verified our calculations by having both a small $S_r$ and minor root biomass.

Overall, the used data shows a variable relation between vegetation characteristics and $S_r$-values in boreal landscapes. This is especially interesting as forestry actions together with shifting vegetation regions towards the north, may thus result in different outcomes for root zone properties. Therefore, future catchment scale studies focusing on the effects of changes in land use or climate on hydrological patterns, should take into account possible changes in $S_r$ as well.

### 4.2 Climate variables

As the root zone storage capacity is derived from climate data, logically a correlation exists between $S_r$ and various climate variables. However, it is interesting to see that not all variables have the same amount of influence (Figure 6). More specifically, the phase difference between the snow-off date (water supply) and onset of potential evaporation (water demand) turns out to be very important.

Further, the different analyses show that for the colder regions, the influence of individual climate variables ($P/E_p$, $T_{AM}$, snow-off date) is more important. This larger influence of climate variables in colder regions can also influence or partly cause the observed threshold behaviour. Combining the predicted change of all these climate variables in the near future in boreal regions (Prowse et al., 2015) with their possible influence on the observed threshold, could indicate a remarkable effect on the hydrological behaviour of northern catchments. This finding for example indicates that earlier snow melt decreases soil moisture during summer, resulting in larger root zone storage capacities. A possible increase in root zone storage capacity with increasing annual temperature and declining snow cover may cause also substantial changes to biogeochemical cycles (Wrona et al., 2016) and generated stream flows (Bring et al., 2016). It would therefore be interesting to extend this research to other boreal and temperate regions. In such a study it can be investigated if this threshold occurs in many areas with energy constrained evaporation or that it is mainly linked to the (non-)existence of snow cover.

### 4.3 Influence of peatlands

When considering different land cover types, it can be seen that especially a higher occurrence of pristine peatlands has a strong influence on the derived root zone storage capacity. In case of more than 20% peatland cover, $S_r$ does not exceed the (again same) threshold of 115 mm. The threshold behaviour is even strongest for the relation between pristine peatland cover and $S_r$.

This may indicate that the "below threshold" conditions are ideal for the development of peat lands, which makes sense as peatlands develop in areas where precipitation exceeds evaporation and thus moisture conditions favour creation of peatland vegetation.

Interestingly, the available space for root development in these peatlands is small, due to high groundwater tables and fully saturated soil moisture conditions. However, this is not explicitly accounted for in the $S_r$ calculations. This indicates that the pristine peatlands do not have a high transpiration demand and that evaporation is not excessively increased by high ground water tables. Typically evaporation from peat surfaces is small, especially if the water levels are below the growing sphagnum vegetation (Wu et al., 2010). Peatland drainage for forestry changed this pattern: higher $S_r$ values were observed in areas with larger cover of drained peatlands (Figure 7). This was expected since the motivation for artificial drainage is to create suitable soil moisture conditions for trees and increase forest growth (Sarkkola et al., 2013a). Peatland drainage has shown to have many affects to hydrological processes (ie. low flows, peak flows), which can be partly explained by the change in $S_r$.

### 4.4 Usefulness of climate derived $S_r$

As shown in earlier studies, climate derived root zone storage capacities can be very useful in a modelling study. However, this study compared different effects on this root zone storage capacity, which is a first step in analysing how transpiration influences catchment scale runoff. In this context a climate derived $S_r$ is especially valuable, as it will change when the climatic conditions (ie. amount of precipitation, snow-off date) or vegetation properties (ie. transpiration pattern) change. Extending this line of thought, a climate derived $S_r$ can possibly be used to assess the hydrological effect of future changes in climatic and land cover conditions and the consequences for biogeochemical processes. This is essential in a global perspective, but especially in boreal regions which are facing drastic changes in near future resulting from joint pressures of intensified land use and climate change.

## 5 Conclusions

This paper showed that the climate based method to derive root zone storage capacities, with a snow component included, can be well applied to a range of boreal catchments. Subsequently, this paper tested the influence of different controls on the developed root zone storage capacity. A climate derived $S_r$ was compared with vegetation characteristics, climate variables and land cover types. A comparison between $S_r$ and the vegetation characteristics showed in general a positive correlation between $S_r$ and leaf cover, tree length and root biomass. This comparison had not been carried out before and further support the plausibility of the climate-based method; additionally, it confirms the suitability of the method to determine $S_r$-values for boreal regions. Another important finding is that especially the (non-)coincidence of the snow-off and the onset of potential evaporation has a large effect on the derived $S_r$. In the studied regions, where evaporation is energy constrained, these two are the main variables determining the demand and supply of water. Further it was observed that catchments with a large pristine peatland cover have small $S_r$ values and that for colder regions the influence of individual climate variables on $S_r$ is larger. A climate derived $S_r$, as used in this study, enables reflecting (changes in) climatic and vegetation conditions in a hydrological parameter. Therefore it gives additional information about the hydrological characteristics of an area and it could be beneficial to assess the effects of changing conditions.

*Data availability.* All data used for this study originates from open access databases which are listed in the data use subsection

*Competing interests.* The authors declare that no competing interests exist.

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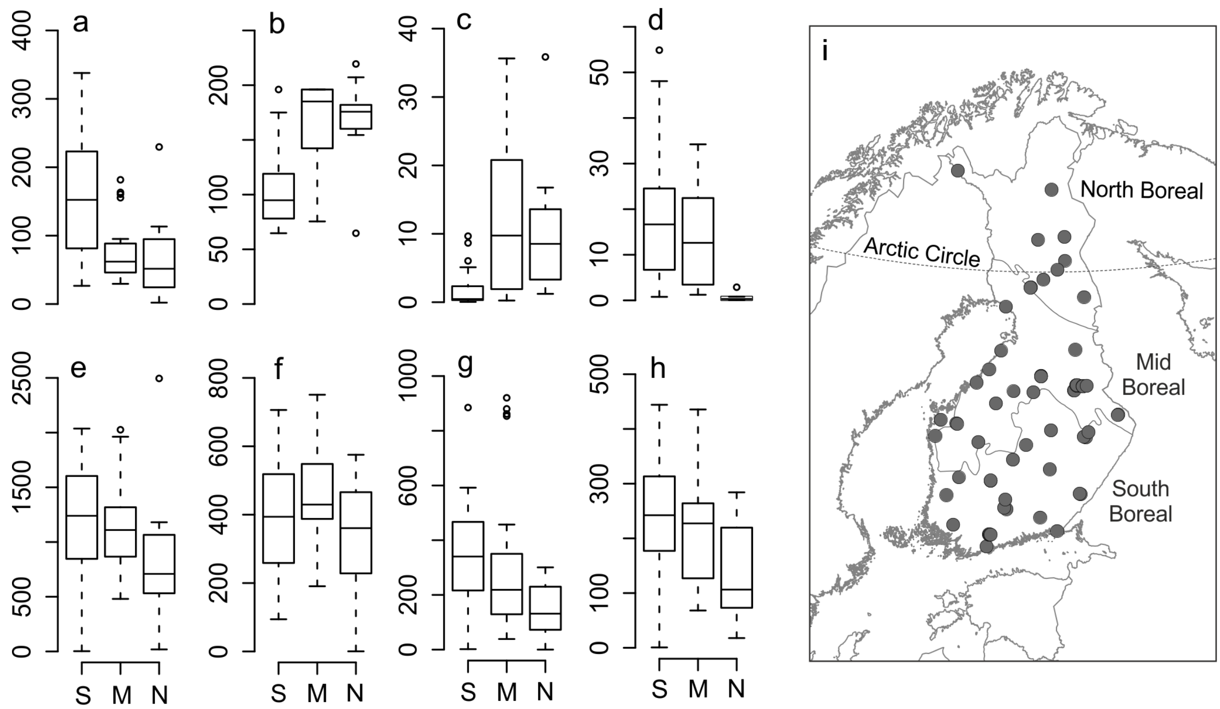


**Figure 1.** a) Root zone storage (mm), b) maximum snow water equivalent ($S_{SWE}$, mm), c) percentage of pristine peatlands (%), d) percentage of agricultural areas (%), e) total tree root biomass (10 kg/ha), f) pine root biomass (10 kg/ha), g) spruce root biomass (10 kg/ha), h) deciduous root biomass (10 kg/ha) at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal).

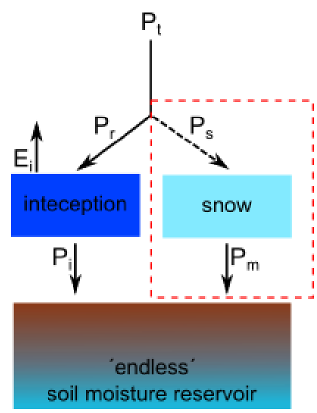


**Figure 2.** Schematisation of the method to calculate Sr, including snow module; the part in the red square is added for this research, the 'endless' soil moisture reservoir is similarly to the one in de Boer-Euser et al. (2016). The arrow for $P_s$ is dashed as this flux is not actually calculated, but $P_m$ is derived from the change in $S_{SWE}$.

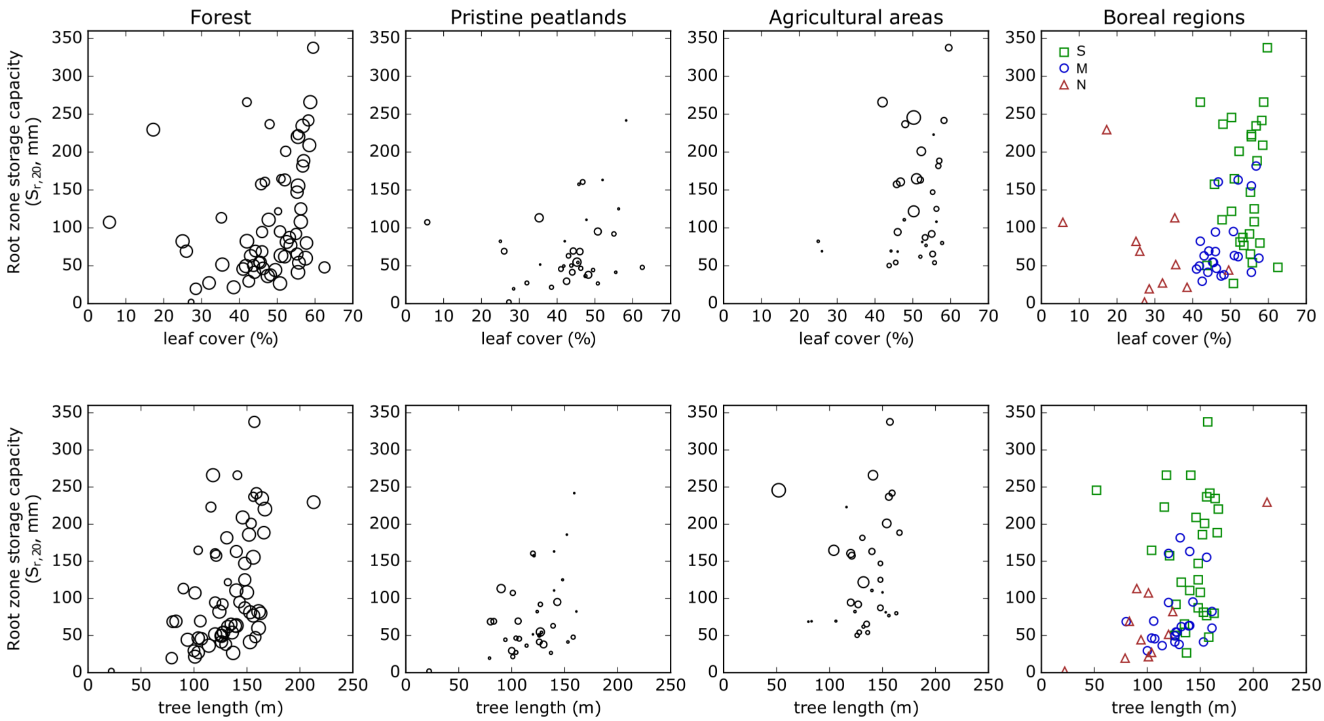


**Figure 3.** Calculated root zone storage capacity versus average leaf cover (top) and tree length (bottom) of four years. Larger circles indicate higher percentage of land cover for a&e) forest, b&f) pristine peatlands, c&g) agriculture; d&h) are colour coded by boreal region.

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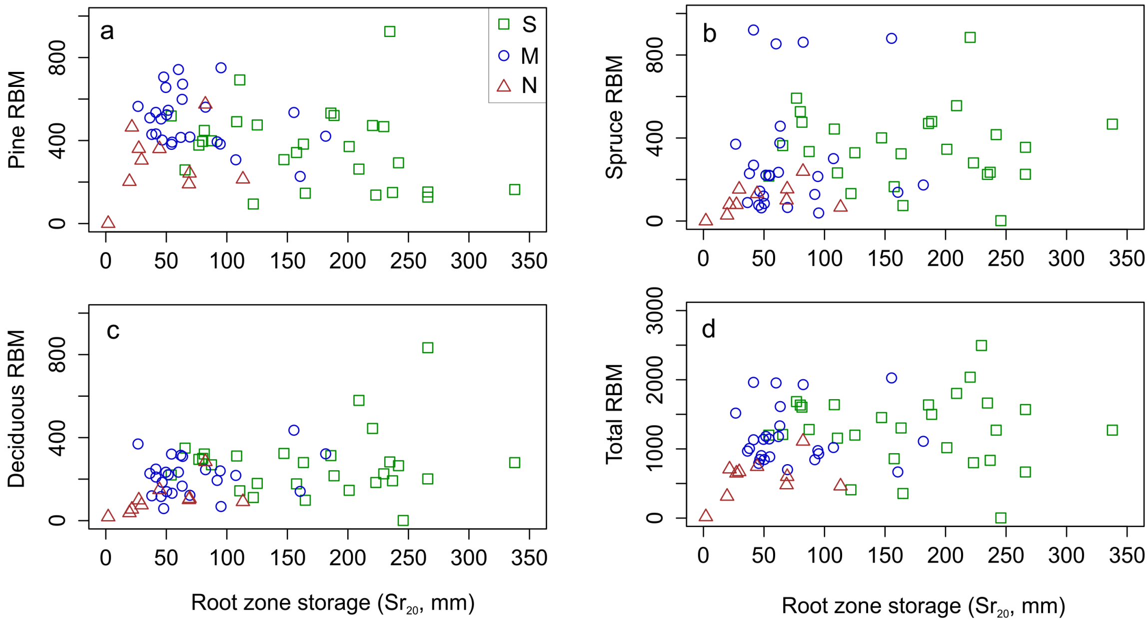


**Figure 4.** Root zone storage capacities and a) pine root biomass (RBM), b) spruce RBM, c) deciduous trees RBM and d) total RBM in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal).

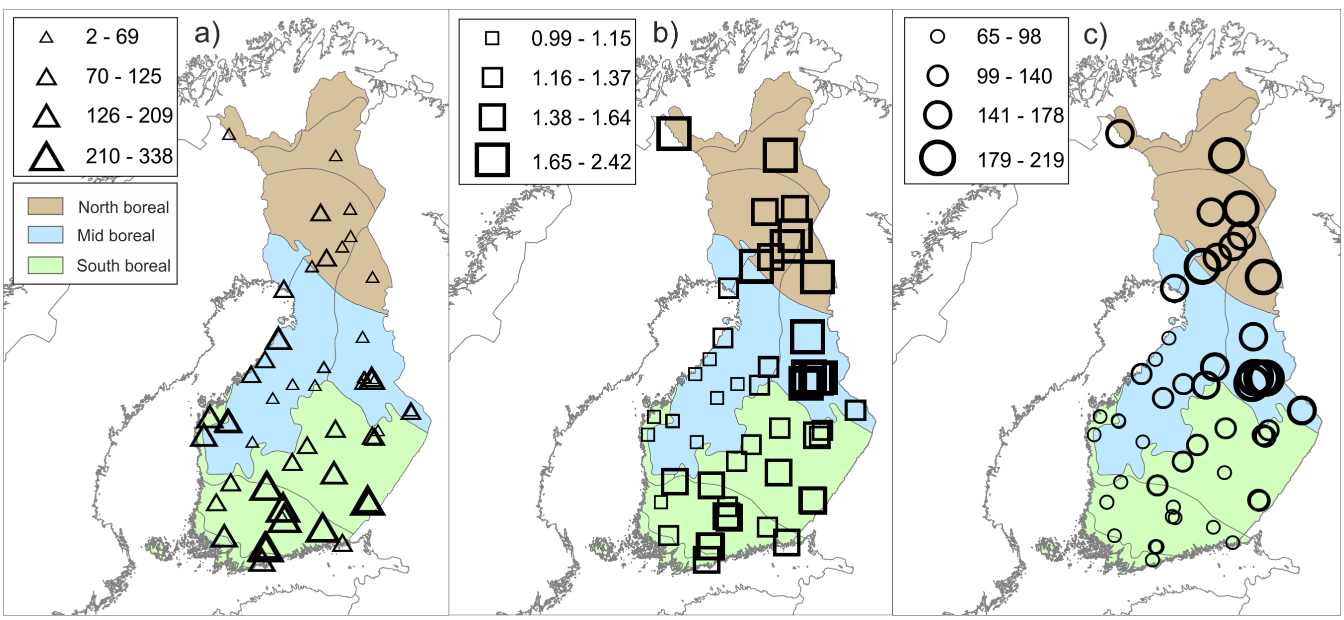


**Figure 5.** Map with study site location and a) calculated root zone storage values ($S_{r,20}$), b) ratio of precipitation and potential evaporation, and c) maximum snow water equivalent ($S_{SWE}$). Different boreal ecoregions (south boreal, mid-boreal and north boreal) are shown in colors and subdivision of ecoregions is marked with gray lines.

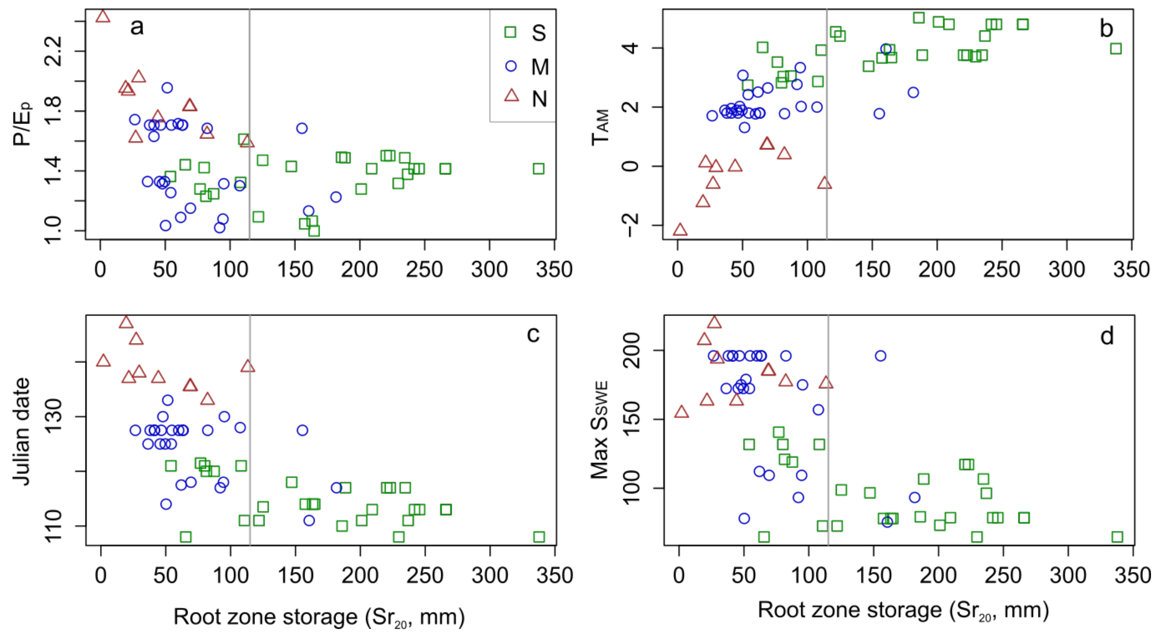


**Figure 6.** Root zone storage capacities and a) ratio of average precipitation and potential evaporation ($P/E_p$), b) mean annual temperature ($T_{AM}$), c) Julian date for snow off, and d) maximum snow water equivalent ($S_{SWE}$) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The line at 115 mm illustrates the discussed threshold.

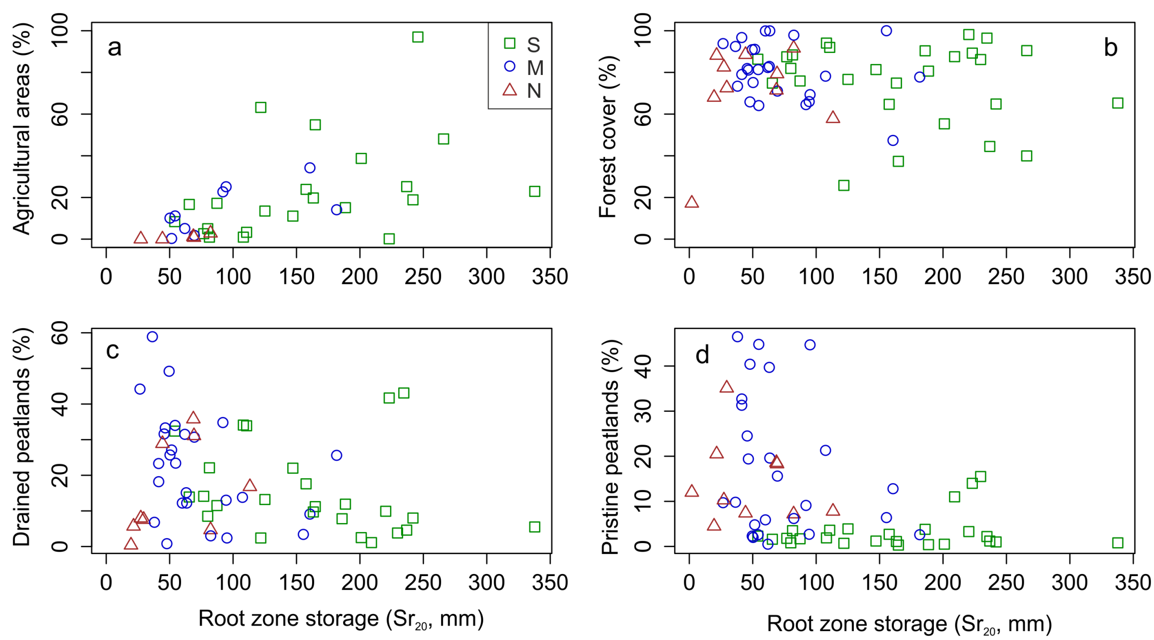


**Figure 7.** Root zone storage capacities ($S_{r,20}$, mm) and proportion of a) agricultural areas (%), b) forest cover (%), c) drained peatlands (%) and d) undrained peatlands (%) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal).

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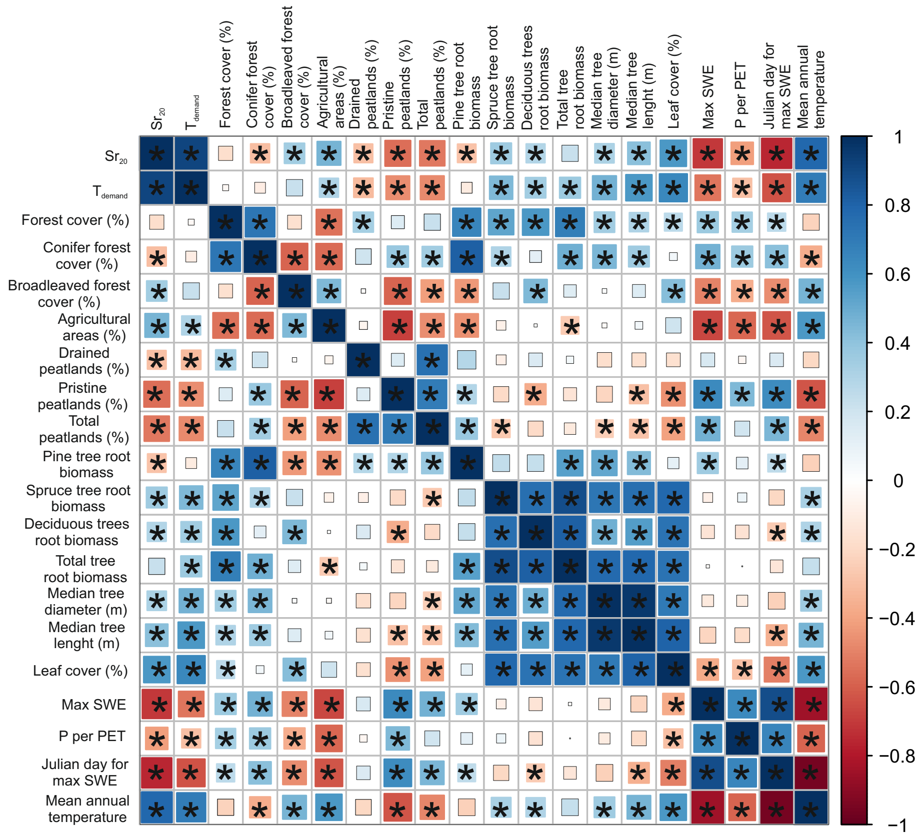


**Figure 8.** Correlation matrix for calculated root zone storage capacity (20 year return period), calculated transpiration demands (used in the $S_r$ calculation) and catchment characteristics. The asterisks indicates a significant correlation (p<0.05).

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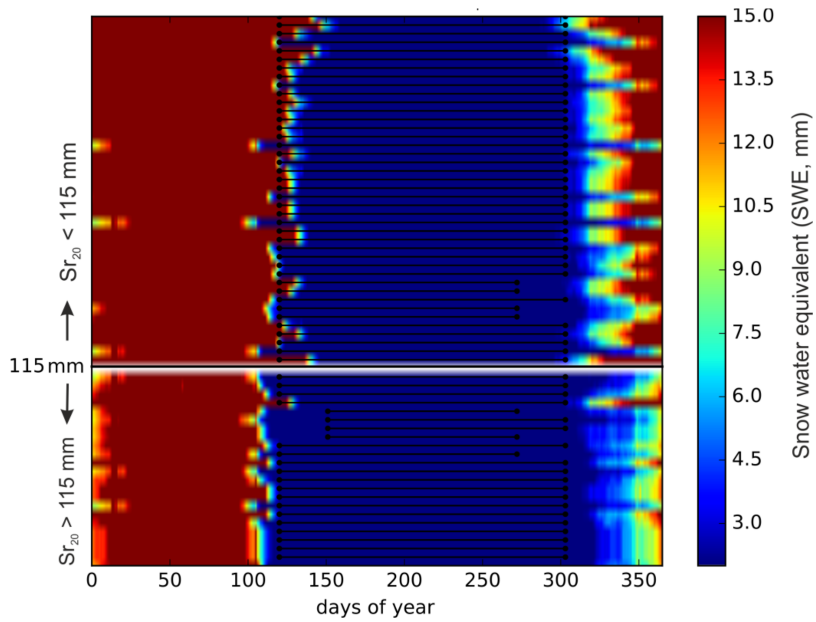


**Figure 9.** Coincidence of snow cover (colour plot) and occurrence of potential evaporation (black lines); presented data are long term daily averages. $S_{SWE}$ is cut off at 15 mm to better visualise the changes in $S_{SWE}$ during snow melt and accumulation.