Author's response for review process of "Understanding variability in root zone storage capacity in boreal regions"

by Tanja de Boer-Euser, Leo-Juhani Meriö, Hannu Marttila

Dear editor,

Please find attached the second revised version of our manuscript. The additional comments of the reviewers have been very useful for this revised version. This document first contains a point-to-point reply to all their comments. The point-to-point reply is followed by a marked-up version of the revised manuscript and supplement.

The most important change in the manuscript is the location of the presentation of the PCA results. These are now located after the presentation of the comparison of S_r with vegetation types. Further, textual clarifications have been made, especially in the discussion section.

We would like to submit this second revised version for the next step in the review process.

On behalf of all authors,

Kind regards,
Tanja de Boer-Euser

1 Reply to review of Maik Renner

Dear Maik Renner,

Thank you for the evaluation of our revised manuscript and the remaining constructive comments. We have replied to your comments below and incorporated them in the latest version of the manuscript.

The authors did a thorough revision of their manuscript with improvements in many aspects. The authors also responded to all concerns raised by me and the other two reviewers.

1.1 Overall comments:

There is, however, one major point which must be addressed in a another revision of the manuscript. It is about the order of the figures and the results. I cannot understand why Fig 1 showing the derived Sr values is mentioned in the methods sections while this clearly a result of this study. Furthermore, the first section in the results is called "dependencies" which is quite unspecific. I would suggest to order Figures and results in a more classic way. For example starting with the scheme of the method as first figure and a map of the region as second figure.

The results should start with the maps of the derived Sr values (note the spatial coherence) and the strong differences when looking at the different boreal regions. After this the correlations to climate, vegetation, etc can be shown. The PCA then nicely summarizes the link of all the catchment characteristics to the new catchment storage estimate.

Such a reorganization is feasible and therefore I recommend a minor revision. It would clearly improve the presentation of the results.

Thank you for this suggestion, we agree that the results are indeed more logically presented if the PCA is moved to after the comparisons of S_r with climate variables, vegetation characteristics and vegetation types. So, we have incorporated this change.

However, regarding Figures 1 and 2, we think it is more logical to first present the study area, followed by the details of the method to derive S_r from climate data. However, to keep presentation of the study area and presentation of the results separated, we have removed the derived S_r from Figure 1 and replaced it with forest cover.

1.2 Minor comments:

title sections 2.4.4 and 3.1 Please use a more specific title then dependencies

We have changed the titles to 'Correlations among catchment characteristics'

PCA methods and results: It should be noted how the PCA was set up, I believe across all catchments. Also report the explained variance of the first two PCA's. This is important to see how relevant the specific features are.

Yes, the PCA was set up across all catchments, we have clarified this in the text, together with mentioning the combined explained variance (54%) of the first two principal components. Further we have added a table to the supplementary material containing the explained variance of the first two principal components and the loadings of all used characteristics on the first two principal components.

P5L20: The choice of the 20 yr return period is quite ad-hoc. Why should it be 20yrs in a boreal region, why should this be constant? I think this is an assumption and it could be worthwhile to discuss the implications of this assumption in the discussion. For example by how much would results change when a different return period is assumed? Does a return period of 20yrs make sense for a agriculturally dominated catchment? Actually Section 4.3 starts with such a discussion but does not link it with the return period.

Thank you for this comment. The 20 year return period is indeed an average we selected for this study, following the results presented by Gao et al. (2014) and Wang-Erlandsson et al. (2016). For catchments with a large agricultural cover, a smaller return period would be more realistic. However, only 3 of the 64 catchments have more than 50% agricultural cover and 8 of the 64 have more than 25% agricultural cover. Therefore, we think using different return periods in this study will mainly increase the amount of variables, without changing the results substantially.

Having said this, the selected return period has an effect on S_r-values derived for the individual catchments, so should be discussed in the discussion of the manuscript. We have done this is Section 4.3.

Fig 4: maps of Sr. The background colors of the 3 regions is visually more pronounced than the Sr values which are shown by the size of the labels. Maybe also use color for the Sr values and only use dotted lines to disentangle the different regions.

Thank you for this suggestion, we have changed the figure accordingly.

FIG 7. Legend for point size is missing

We have added a legend for the point sizes to the figure.

2 Reply to review of anonymous referee #1

Dear referee,

Thank you for the evaluation of our revised manuscript. Your additional comments were valuable for the latest version of our manuscript. However, considering the mentioned line numbers, we have the feeling you have reviewed the first version of the manuscript again, after reading our replies to your comments and those of the other referees. We have replied in detail on your comments below; those not already incorporated in the previous version of the manuscript are now incorporated.

2.1 Overall comments:

The authors have come back with an improved manuscript that addresses many of the comments and concerns raised in the initial assessments. I am recommending publication but still believe that some changes are necessary. I am not sure that the authors have established "control" (i.e. page 1 line 5) versus "correlation", especially given the intrinsic relationships and correlations between the variables used in calculating Sr,20 and the assessment. I do appreciate the analysis conducted and do not dismiss the results. I believe there may be merit in the hypothesis, which warrants future studies in different locations. I don't believe it is necessary to come to a strong conclusion in this paper. What I would like to see is a more frank discussion of the caveats and limits to what has been presented, but with a view towards the possibilities associated with extensions of this work, which may indeed prove useful.

Thank you for your evaluation. In this version we have elaborated some elements in the discussion further.

2.2 Specific Comments:

Figure 7: There appear to still be inconsistencies in the data presented. In the mid-boreal region there is a catchment with almost 60% drained peatland and Sr,20 of around 40 mm. However, while there are some points representing pristine peatlands with a similar Sr,20, there are no corresponding lower percentage points for forest cover and agricultural areas. I am speculating that that there are some zero points or points very close to zero that are not shown. Where are the corresponding fractions of forest and pristine peatlands for these points? There apper to be other such examples. The removal of zero or near-zero points (some or all?) might be biasing the interpretation of results. Am I reading the plots incorrectly?

Both in Figures 6 and 7 (numbering according to latest version of the manuscript) all catchments are now included in all subplots, so also if a certain vegetation type is not present in the specific catchment.

Page 6 line 20-21: I suspect that the correlation between Sr,20 and leaf cover or tree length for the entire dataset is better than for any of the three regions. It appears that the forest structure follows a rough latitudinal gradient (the authors have noted climate effects in both directions in their previous response). Separating the data into regions defined by latitude makes the relationships harder to see because some of the main drivers associated with latitude are excluded. The figure does not need to be changed but this point could be added.

The correlation coefficients for the different comparisons are now mentioned with the figures. A stronger correlation is indeed present when all catchments are considered; we have discussed this in Section 4.1.

Page 6 lines 25-27: Figure 4 may be showing the 'preference' of spruce, pine and deciduous trees. Pines often locate on sandy or rapidly draining soil, which has a small Sr because the difference between field capacity and the wilting point is small. Pines do not grow well in wet soils so the largest root biomass is likely found where they grow well. Spruce trees do not grow as well in sandy dry areas so the largest root biomass is found in the areas with more moderate drainage. In the north where there are thick peat soils, these soils developed because of the persistent poor drainage and high water table (and slow decomposition). If the peat soils did not dry out during the 20-year drought periods, they will have small estimated Sr,20 values and since trees do not grow deep roots in waterlogged soils this creates an association with trees in low Sr,20 regions having a low root mass, except for pines which are in areas with a small Sr,20 for different reasons described above. I see this sort of discussion as helpful in understanding the multi-facetted relationship between the climate, soil, hydrology and vegetation, rather than implying undue control by vegetation.

Thank you for this analysis, we have discussed this multi-facetted relationship further in sections 4.2 and 4.3 of the revised manuscript.

Page 7 line 15-17: The words "leads to" implies causation which I am not sure exists. I suggest changing "leads to" to "is associated with" which is softer and less open to criticism. Some discussion about causal relationships and correlation is warranted in the paper overall. Tree growth is affected by seasonal and annual temperatures as is evaporation, rain/snow partitioning and the snow off date.

The mentioned sentence is no longer present in the revised manuscript.

Page 7 line 23-24: I am not asking for these to be answered directly but the authors might consider them and add to the discussion only if relevant to this region and the results. What role do natural drainage (or lack hereof) caused by soil depth, soil texture or topography and the effect of temperature on evapotranspiration play in the Sr,20 values? Is Sr,20 greater in the south because evaporative demand is higher and forest cover smaller because the forests were cleared and/or planted on drained peatlands? Are forested peatlands classified as forests or peatlands? I have read that many of the drained peatlands were planted as forests. In which category are these included?

As S_r is derived from climate data, the effect of temperature and evaporation is large. As argued during the previous revision, the used method assumes equilibrium in the catchments. Apparently, the vegetation was able to survive given the occurring precipitation and evaporation, and thus runoff generation in the catchment. To do this, it created a sufficient buffer with its root system. Ground water table levels, soil depth, soil texture and topography likely determine how this root system was developed, but too a much smaller extend its size (ie., its buffer capacity). In our study we only took into account the estimated buffer capacity of the root system as a catchment representative characteristic. It was beyond the scope of the study to consider its internal structure.

Evaporation is higher in the south boreal region because of higher potential evaporation, but forest cover is also higher in the south boreal areas. Our catchments did not contained any large forest cutting areas. In

Finland the majority of peatlands has been drained for forestry purposes. In our study, all forests are clasified as 'Forests'; the drained peatlands in Figure 8 can contain forest, but can also contain other vegetation types. We have clarified this in Sections 2.4.2 and 2.4.3.

Page 8 line 11-19: I present this as an alternative to the threshold interpretation. For catchments with more forest, the snowpack is sheltered by the forest and the snow melts later but the air temperature is warmed by the dark canopy albedo. So the snow in the northern forest probably melts at warmer (weather station) air temperatures than in the south. I suspect that the evaporation pans are generally placed at weather stations located in the open, not under the shelter of forests, so they will experience the warmer air (relative to the cold sub-canopy air) and Ep will start while the snow is still on the ground under the canopy. Where there is less forest the more exposed snow melts faster and more in-line with increases in air temperature and solar radiation and is gone before Ep becomes significant. I am not certain whether the differences in forest cover are enough to be the main driver of this apparent relationship with Ep and Sr,20 but if it contributes it supports softening the conclusions.

We agree with hypothesis and it should be valid when compared with catchments within the same climate region (eg. catchments within the southern boreal). Furthermore, to test this hypothesis the comparison should include catchments with full forest cover and catchments with heavy forestry operations (clear cutting). In these circumstances canopy albedo differences and accumulation of snow start to influence on snow melting conditions and further probably to E_p conditions. Nevertheless, in our catchments we did not have the possibility for this comparison and the main driver in maximum S_{SWE} values and E_p was the difference in climate across the regions. One should observe that climate varies notable in Finland from south to north (from temperate to sub-boreal conditions) which dominates variability between the catchments.

In addition to this, we have discussed the possibility that the threshold is the result of a measurement artifact (Section 4.1) and what would be the consequences of this for using S_r to assess hydrological effects of changing climatic and vegetation conditions (Section 4.4).

Page 8 line 21: I believe correlation has been shown and the results are intriguing but I don't believe causation has been successfully argued.

During the first revision of the manuscript we have removed the term 'control' from the manuscript, as we have indeed more investigated correlations and no causal relations. Further, in Section 4.2 we discuss that we assume the vegetation to be in balance with the transpiration demand, but that not necessarily one is causing the other.

Page 9 lines 1 and 2: The sample size of catchments with small agricultural leaf cover appears too small to make inferences about the effect of varying agricultural leaf cover. However, I am wondering where the zero values are? Are there no catchments with zero or near-zero agricultural cover, zero or near zero pristine peatlands?

This paragraph is no longer present in the revised version of the manuscript.

Page 9 lines 6-9: While the authors do acknowledge that the density of pine trees may be too low in these catchments to have much influence on transpiration and storage, I still feel that the preceding statement goes too far. The authors do not present any information about the percentage or proportion of leaf cover or tree *cover that is represented by pine, spruce and deciduous species. Are the RBM values calculated on a catchment basis, such that the sum of root biomass for each species in each catchment is divided by the entire area of each catchment, or is the root biomass merely the average for each species within the areas that contained that species (i.e. within sub-areas of each catchment, the fractions of which we do not know)? If these RBM values are averaged over the area of the catchment, then I would interpret Figure 4a as showing that pine do not grow well in catchments that have a very high or very low Sr,20. A very low Sr,20 might indicate a lack of sufficient soil, or perpetually water-logged conditions, such that all trees grow poorly. At slightly greater but still small Sr,20 values, we may see the sandy areas favoured by pines represented; they grow well but need a high root biomass to access enough water in the rapidly draining sandy soil. As Sr,20 continues to increase, we likely encounter conditions in which the soil is wet enough of the time that spruce and deciduous species outcompete pine.*

Thank you for this suggestion and argumentation. The root biomass values are indeed averaged over the entire area of the catchment. The mentioned statement is no longer present in revised manuscript, but we have discussed this aspect at the end of Section 4.2.

Page 10 line 4-7: Yes, the boreal ecosystem has been referred to as a "green desert". (Hall, 1999, `https://doi.org/10.1029/1999JD901026`*; Betts et al. 2001, 2001 JD900047). There is ample water on the surface but either because of nutrient limitations or adaptation to cool environments, the vegetation is less productive and evaporation rates are generally low.*

Thank you for this suggestion. We have mentioned the concept of "green desert" and the suggested references in the beginning of section 4.

Page 10 line 16-18: The authors should expand on this idea of a climate-derived Sr,20 being useful to assess the hydrological effect of future changes in climate and land cover. This point could provide justification for this work. Can the authors discuss what would be required for this to happen? Additional studies need to be conducted to assess the usefulness of a climate-derived Sr,20 and its applicability in different locations. Then, this could be evaluated in models of sufficient complexity, and if the patterns are similar, in climate change scenarios. At this stage, stating that this method is useful is conjecture, but pointing to work that would serve to test this would set this paper in a better context.

Thank you for this suggestion for a better framing of the usefulness of a climate derived S_r to assess the hydrological effects of changing climatic and vegetation conditions. We have expanded the last paragraph of section 4.4.

2.3 Corrections:

Page 1 line 3: Change "enables to account" to "enables one to account".

We have changed the sentence accordingly.

Page 1 line 11: Change "besides from" to "apart from".

We have changed the sentence accordingly.

Page 1 line 20: change "alter magnitude" to "alter the magnitude".

We have changed the sentence accordingly.

Page 1 line 23: Change “in near future” to “in the near future”.

We have changed the sentence accordingly.

Page 1 line 24: Awkward sentence. Change “The occurring land use changes consist of” to “These land use changes consist of”.

We have changed the sentence accordingly.

Page 2 line 2: Change “as source for biomass” to “as a source of biomass”.

We have changed the sentence accordingly.

Page 2 line 5: I am not sure what the authors mean by “measures”.

We have replaced ‘measures’ with ‘land use activities’.

Page 2 line 21: Change “boreal catch” to “boreal catchments”.

We have changed the sentence accordingly.

Page 3 line 2: Change “Characteristics study catchments” to “Characteristics of study catchments”.

We have changed the header accordingly.

Page 3: There are a number of very short paragraphs, some of which could be combined.

We have combined the last two paragraphs. The other ones we prefer to keep separate, as they treat different aspects of the study catchments.

Page 3 line 5: Change “belong to National network” to “belong to a national network”.

We have changed the sentence accordingly.

Page 3 line 13 and 14: Change “sites” to “catchments”. Unless a specific field measurement location is referred to, the use of ‘catchments’ is preferred over ‘sites’ because ‘sites’ suggests specific locations in space, and I believe all of the data are presented at the catchment scale.

We agree with you that ‘catchments’ is preferred over ‘sites’ and have changed this throughout the manuscript.

Page 3 line 22: Change “additional data were used about leaf cover” to “additional data were used, including leaf cover”.

We have changed the sentence accordingly.

Page 4 line 1: Change “data was available” to “data were available”.

We have changed the sentence accordingly.

Page 4 line 2: Change “from Finnish” to “from the Finnish”.

We have changed the sentence accordingly.

Page 4 line 6: Change “data was adjusted” to “data were adjusted”.

We have changed the sentence accordingly.

Page 5 line 6: Change "sevaral" to "several".

In the revised version of the manuscript this sentence is changed and the word is no longer there.

Page 10 line 11: Change "affects to" to "effects on".

We have changed the sentence accordingly.

Figure 6a: The use of the term Julian day is not correct. It should be day of year. The authors indicated that this would be corrected but have not done so.

We have corrected this in the figures and text.

3 Marked-up manuscript

The following pages contain both the manuscript and the supplement with all changes marked.

Understanding variability in root zone storage capacity in boreal regions

Tanja de Boer-Euser[1,2], Leo-Juhani Meriö[3], and Hannu Marttila[3]

[1]Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, NL-2600 GA Delft, The Netherlands

[2]Department of Civil Engineering, Eduardo Mondlane University, C.P. 257 Maputo, Mozambique

[3]Water Resources and Environmental Engineering Research Unit, PO Box 4300, 90014 University of Oulu, Finland

Correspondence: Tanja de Boer-Euser (tanjaeuser@gmail.com)

Abstract. The root zone storage capacity (S_r) of vegetation is an important parameter in the hydrological behaviour of a catchment. Traditionally, S_r is derived from soil and vegetation data. However, more recently a new method has been developed that uses climate data to estimate S_r based on the assumption that vegetation adapts its root zone storage capacity to overcome dry periods. This method also enables one to take into account temporal variability of derived S_r-values resulting from changes in climate or land cover. The current study applies this new method in 64 catchments in Finland to investigate the reasons for variability in S_r in boreal regions. Relations were assessed between climate derived S_r-values and climate variables (precipitation-potential evaporation rate, mean annual temperature, max snow water equivalent, snow-off date), detailed vegetation characteristics (leaf cover, tree length, root biomass), and vegetation 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-values. Further to this it is found that (non-)coincidence of snow melt and potential evaporation could cause a division between catchments with a high and a low S_r-value. It is concluded that the climate derived root zone storage capacity leads to plausible S_r-values in boreal areas and that ~~besides~~apart 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). Increasing temperatures and precipitation, shifts in precipitation from snow to rainfall and retreating seasonal snow cover are a few examples of alterations of the boreal hydrological cycle (Bring et al., 2016). Consequences of increasing temperatures are likely to be most severe in boreal systems, as slight changes in temperature can alter the 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 the near future due to a “green shift” to a bio-based economy (Golembiewski et al., 2015). ~~The occurring land use changes~~The land use changes consist of modifications in actual 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 a source for biomass (e.g. Laudon et al., 2011; Nieminen et al., 2017).

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~~land use activities. 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), and some already studied changes in transpiration (patterns) at the catchment scale in boreal regions (e.g. van der Velde et al., 2013; Jaramillo et al., 2018). The partitioning between transpiration and runoff is largely determined by the water use efficiency of vegetation (e.g. Troch et al., 2009) and the available root zone storage capacity (S_r) of the vegetation (e.g., Zhang et al., 2001): the water use efficiency determines the amount of water the vegetation needs and the root zone storage capacity ensures sufficient storage to supply this water. Thus, detailed knowledge about these variables 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 layers 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 catchments could benefit from a better understanding of the relation between S_r and climatic and vegetation conditions.

The method to derive S_r from climate data was originally developed to estimate an important parameter in conceptual hydrological models (e.g. Gao et al., 2014). So, influences on the derivation and wider applicability of the climate derived S_r need to be investigated before it can be used to further assess the hydrology of boreal areas and to assist in assessing the hydrological effects of climat~~e~~ic and land use changes. Therefore, this study aims at better understanding the influences of different climate variables on the climate derived S_r-values and its wider applicability by comparing it with various catchment and vegetation characteristics.

2 Methods

2.1 Characteristics of study catchments

A total of 64 headwater catchments were used for this study, 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~~catchments belong to ~~N~~a 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 ~~sites~~catchments in the south and mid-boreal regions. Total root biomass, as well as root biomass for spruce and deciduous trees decreases towards the north, while pine root biomass is more or less constant (Figure 1). 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~~catchments 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~~for 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 variation of S_r. For the S_r calculations daily precipitation, daily snow water equivalent, monthly potential evaporation and yearly discharge data were used. For investigating the variability and relations with catchment characteristics additional data were used~~ about~~, including leaf cover, tree length, root biomass, temperature, snow-off date and ~~land cover~~vegetation type.

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 the Finnish Meteorological Institute (FMI) (Paituli database[c8]). These data have been checked for measurement errors caused by gauges and were corrected in operative quality control. The snow line data for snow water equivalent (S_{SWE}), potential evaporation (E_p), using pan measurements, and runoff data used were obtained from the Finnish Environmental In-

[c8] https://avaa.tdata.fi/web/paituli/latauspalvelu

stitute's open database (Hertta). Note that because E_p is derived from pan measurements, it is not measured when temperatures are below zero. However, it can be assumed that if it would be measured, amounts would be very low.

The snow line measurement points were either located inside or in close proximity of the study catchments; however, 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~~were assumed to be more reliable and less spatially variable, the S_{SWE} data ~~was~~were adjusted on a daily basis to make ~~it~~them consistent with the precipitation data.

Corine Land Cover 2012 data (Paituli database) was used for determining the ~~land cover~~vegetation types occuring in ~~of~~ the study catchments. The surface lithology and geology data are based on the Surface Geology Map of Finland (Hakku database[c5]). Data for root biomass, tree length and leaf cover are based on multi-source national forest inventory data provided by the Natural Resources Institute Finland (LUKE open data[c6]). Data ~~is~~are based on field inventory data, satellite images, digital map data and other georeferenced data sets (for more information refer to Mäkisara et al., 2016). Tree data ~~was~~were available for Pine, Spruce and Deciduous forest types. Drained and pristine peatlands masks were obtained from the Finnish Environmental Institute (SYKE).

2.3 Climate derived root zone storage capacity

To investigate the variability in 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 a severer drought and investing more is not efficient in terms of carbon use. This method results in a catchment representative storage capacity, which reflects the root zone storage capacity for all vegetation combined in a catchment. It is further assumed that the amount of required storage depends on the amount of water that should have transpired to close the water balance. 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). For the calculation of S_r the daily balance between infiltration (I) and transpiration demand (T) is used to simulate the amount of storage the vegetation would need to cover the infiltration deficit.

The transpiration demand used in this method is the amount of water that should, in the long term, transpire to close the water balance. For the calculation $\overline{T}$ was thus derived from the long term water balance ($\overline{T} = \overline{P} - \overline{E_i} - \overline{Q}$); following monthly averaged potential evaporation was used to add seasonality to T. Infiltration was assumed to be the result of precipitation minus interception evaporation in the original calculations (e.g., Gao et al., 2014; de Boer-Euser et al., 2016). 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 the study catchments, a snow component (Equations 1-4) was added to the calculation method. The change in S_{SWE} was used to determine the amount of precipitation stored on and infiltrating into the soil on a daily basis. Interception was only taken into account in case of liquid precipitation and an interception threshold of

[c5] https://hakku.gtk.fi/en/locations/search
[c6] http://kartta.metla.fi/opendata/valinta.html

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.

The estimates for infiltration and transpiration demand were used in a daily simulation of the root zone storage. Infiltration forms the inflow of water and transpiration the extraction; any excess water is assumed to runoff directly. This simulation results in annual required maximum storage capacities, which were used in a Gumbel distribution (Gumbel, 1935) to obtain the required storage capacity to overcome a drougth with 20-year return period. A 20-year return period was selected as an avaraged catchment representative, following~~based on~~ the results of Gao et al. (2014) and Wang-Erlandsson et al. (2016) and based on the high percentage of forest cover in the study catchments.

The method described above estimates S_r for a current situation based on historical drought occurences. However, the same principle and calculation method can be used to estimate S_r under changing conditions. These can be derived from observed data (e.g. Nijzink et al., 2016), but can also consist of scenarios of changing climate variables or land use characteristics. The latter one could be represented by using a different drought return period (e.g. Wang-Erlandsson et al., 2016).

For estimating S_r in this study, 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~~were limitedly available for the study period; for these catchments older discharge data ~~was~~were taken into account as well to obtain a long term average.

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

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

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

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

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

2.4 Relations between S_r and catchment characteristics

To further explore the physical meaning and applicability of the climate derived root zone storage capacity, S_r-values were compared with climate variables, vegetation characteristics and coverage of vegetation types.

2.4.1 Climate variables

The method used to derive S_r is based on climate data, so it is expected that climate has a strong influence on the derived S_r-values. However, the derived S_r-values are not a linear combination of the used variables (i.e. daily P, daily S_{SWE}, yearly Q, monthly E_p) and thus the influence of different climate variables is not straight forward. Therefore, derived S_r-values are compared with four other climate variables (P/E_p-ratio, mean annual temperature, snow-off date and maximum S_{SWE}) to analyse which ones have the strongest relation with the S_r-values. These variables were selected as they are expected to reflect the absolute and phase difference between water supply (precipitation and snow melt) and water demand (transpiration), which is assumed to have the largest influence on the derived S_r-values.

The relations between the estimated S_r-values and climate variables were assessed ~~in two ways;~~ by analysing spatial patterns and scatterplots. To assess the correlation between the different variables, the non-parametric Spearman's correlation coefficient was used.

2.4.2 Vegetation characteristics

The climate derived S_r is originally a parameter for conceptual hydrological models and for that purpose it is expected to reflect a representative storage capacity in a catchment. In that sense it cannot be attributed to a single type of vegetation or be directly measured in the field; despite this, it is expected that it is related to actual vegetation characteristics. When this correlation indeed exists, the climate derived S_r will be more useful to use for other purposes than modelling.

First, 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. Second, 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 height as well.

2.4.3 Vegetation types

Different vegetation types and their corresponding land covers occur in different climates and ecosystems and can have different survival mechanisms. And, a change of vegetation or land cover type is likely to change the transpiration and thus the hydrology of a catchment. Therefore, the relation between S_r and land cover and vegetation types was investigated. The vegetation types included in this analysis are forest (containing all forest types), pristine peatlands, drained peatlands (covered with either forest or agriculture) and agricultural area. The relations between the estimated S_r-values and these vegetation types were assessed using scatterplots between S_r and the vegetation types. The non-parametric Spearman's correlation coefficient was used to assess the correlation between the different variables.

2.4.4 DependenciesCorrelations among catchment characteristics

The catchment characteristics that were compared with the climate derived S_r are very likely to be correlated, making it difficult to assess their individual relation with S_r. A principal component analysis (PCA) was usedset up across all catchments to explore the dependencies between the used characteristics. A PCA is a statistical tool which can be used to reduce the dimensions of a problem and explore correlations between variables.

Before carrying out the PCA, the end products were standardised to have zero mean and unit variance on the covariance matrix. The final number of principal components (PCs) was determined using the broken-stick model (Jackson, 1993), in which eigenvalues from a PCA are compared with the broken-stick distribution. Since each eigenvalue of a PCA represents a measure of a component's variance, a component was retained if its eigenvalue was larger than the value given by the broken-stick model. Numerical results of the PCA can be found in Table 3 in the supplementary material.

3 Results

3.1 Climate variables

Derived S_r-valuesroot zone storage capacities were compared with a set of climate variables reflecting the absolute and phase difference between water supply and demand. Focussing first on the relation between S_r and the absolute difference, Figure 3 shows the spatial patterns of S_r and P/E_p (a definition of the aridity index). 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 4a: 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 no significant correlation exists: the range in S_r-values is large, although the variability in P/E_p is small.

Second, snow cover (expressed in snow water equivalent, S_{SWE}) is important when focussing on the phase difference between water supply and demand. With more precipitation being stored for longer periods the supply of water will be delayed. Figure 3 shows for the majority of the catchments higher derived S_r-values (a) in case of lower maximum S_{SWE} (b). However, for some catchments in the mid-boreal region very small S_r-values are derived while maximum S_{SWE} is not very high. As al-readyalso discussed in section 3.4 and shown in Figure 8 P/E_p and S_{SWE} are correlated. Especially, both E_p and snow storage and melt are driven by temperature. Figure 4 shows the strongest correlation between mean annual temperature (T_{MA}) and S_r, followed by snow-off date, maximum S_{SWE} and P/E_p. This indicates that for the studied catchments the phase difference as well as the absolute difference between water supply and demand are important, with the first one probably having a larger influence.

3.2 Vegetation characteristics

Estimated root zone storage capacities were compared with ~~vegetation~~ characteristics of the vegetation in the study catchments. In Figure 5 S_r is compared with the observed root biomass in the catchments. A distinction is made between three types of trees: pine, spruce and deciduous trees. Root biomass of spruce and deciduous trees is positively correlated with S_r when considering all catchments; when considering the individual boreal regions, only a significant correlation exists for deciduous trees in the north boreal region. The correlation between S_r and root biomass of pine is very interesting: a negative correlation exists between S_r and root biomass when considering all catchments. For the individual regions no significant correlation exists~~: t~~This finding indicates that more storage is created with less or thinner roots. Figure 5d combines the results for all tree types and shows in general higher S_r-values for higher densities of root biomass, but this correlation is not significant.

Figure 6 shows the relation between S_r and average leaf cover (top row) and tree height (bottom row). For both comparisons the data is plotted indicating the occurence of different vegetation types (forest, pristine peatlands and agriculture) in the catchments and the boreal regions in which the catchments are located. S_r is positively correlated with both leaf cover and tree height (Spearman's coefficients of 0.33 and 0.32 respectively), but no significant correlation exists for the individual boreal regions. When looking at the different vegetation types, it can be seen that catchments with a large forest cover are the ones with the widest range in leaf cover and tree ~~length~~height. Especially for catchments with a large agricultural cover this range is smaller. More details about the relation between vegetation type and S_r are discussed in Section 3.3 and Figure 7.

3.3 Vegetation types

In addition to climate and vegetation characteristics, also vegetation types can have an influence on the derived S_r, mainly because different vegetation types have different transpiration patterns and survival strategies. Before analysing correlations between S_r and vegetation type, it should be noted though that ~~these~~vegetation types are (partly) correlated with climate as well (Figure 8). This is especially relevant for the correlations between S_r and (pristine) peatlands and agriculture.

The strongest correlation between S_r and vegetation types can be found for agricultural covers; here not only a significant positive correlation is present when considering all catchments, but also for the three individual regions (Figure 7). Further, a decrease in forested area coincides with a larger range in S_r, but no significant correlation is found, neither for all catchments and for the individual regions (Figure 7b). The drained peatlands (Figure 7c) also show a negative correlation with S_r when considering all catchments and for the mid-boreal region: for the north and south boreal regions no significant correlations were found. While for the former three vegetation types a stronger or weaker gradual relation with S_r can visually be observed, the pristine peatlands show strong threshold behaviour. For catchments covered for more than 20% with 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.

3.4 ~~Dependencies~~Correlations among catchment characteristics

[this was section 3.1 in the previous version of the manuscript]The variables that were compared with S_r are very likely to be correlated among themselves as well. Therefore, Figure 8 shows a principal component analysis based on the catchment characteristics used in the analysis. Figure 8a shows the individual catchments with their loadings on PC1 and PC2 (with a combined explained variance of 54%); Figure 8b shows the same for the catchment charactersitics used in the comparison. The plotted catchments (~~top plot~~a) indicate that the eco-regions mainly differ in climate characteristics and that especially in the mid- and south boreal regions a large range of vegetation characteristics and vegetation types occur.

Figure 8b shows that the majority of the climate variables (shown in blue) are positively correlated to each other and negatively correlated to the mean annual temperature and transpiration demand. What can also be seen is the limited correlation between the majority of the climate variables and (summer) precipitation. With respect to vegetation characteristics (shown in green), these are strongly correlated with forest and agricultural land covers, but limitedly correlated to the majority of the climate variables. Only peatland covers are positively correlated with the majority of the climate variables.

Especially, the relative independence of the vegetation characteristics and vegetation types with respect to the climate variables is important to keep in mind ~~for the remainder of the analysis~~when interpreting the results. This means that relations between S_r-values and vegetation characteristics are not likely to be strongly influenced by the climate variables.

3.5 Threshold behaviour

The results presented before show to a variable extent a threshold in the relation between the derived S_r-values and the catchment characteristics. This threshold is mainly visible in Figures 4 and 7d and seems to be the strongest for snow characteristics (Figure 4c,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 pristine (U-test, p=0.0008) and drained (U-test, p=0.0135) peatlands. At the same time also climatic parameters changed: P/E_p (U-test, p=0.0264), max S_{SWE} (U-test, p=0.0000), snow-off date (U-test, p=0.0000) and mean annual temperature (T_{MA}: U-test, p=0.0000) showed a significant difference between the groups.

As not only the maximum S_{SWE} and T_{MA} ~~are important~~show a strong correlation with S_r, but also the snow-off date (Figure 4), 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 (colour plot) and the period in which potential evaporation is above zero (white lines) 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. The phase difference between snow-off and onset of E_p was calculated and included in Figure 8; it is positively correlated with the majority of the other climate variables. It is therefore likely to show the combined effect of the different climatic influences. This phase difference gives an explanation for the origin of the threshold, but not for 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 among the compared characteristics the climate derived root zone storage capacities are strongest related to climate variables, followed by vegetation characteristics and vegetation types. These results gain better understanding of the influence of the different climate variables on the calculation of S_r in snow dominated regions. ~~Moreover, they~~The boreal ecosystems has been referred as a "green desert" (e.g. Hall, 1999; Betts et al., 2001); although ample water is available on the surface, the vegetation is less productive and evaporation rates are generally low, because of either nutrient limitations or adaptation to cool environments. Our results can thus ~~can~~ be used to explore the physical meaning and wider application of S_r ~~from~~for land and water management purposes. Below, possible reasons for differences in correlation and for the found threshold are discussed, together with implications of the findings.

4.1 Climate variables

As the root zone storage capacity is derived from climate data, logically a correlation exists between the derived S_r-values and various climate variables. The strongest correlations between S_r and the catchment characteristics are found when all three boreal regions are considered together and to a lesser extend when the boreal regions are considered individually; these boreal regions mainly differ in climate characteristics (Figure 8). Together with the results presented in Figure 4 this shows that the relation between climate and S_r is stronger than the relations between S_r and other catchment characteristics.

However, it is interesting to see that not all climate variables have the same ~~amount of~~ influence (Figure 4) on the derived S_r-values. 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 (Figure 9). Although the current (non)coincidence of snow-off and the onset of E_p could partly be attributed to the measurement techniques and locations of both variables, it still shows that the derived S_r-values are sensitive to the phase difference between the two. Further, the different analyses show that for the colder regions, the influence of individual climate variables (P/E_p, T_{MA}, 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.

4.2 Vegetation characteristics

Figure 8 shows that the vegetation characteristics are not strongly correlated with the majority of the climate variables, which makes it interesting to compare them~~ir patterns~~ with ~~those of~~ S_r. However, the result of this comparison did not show patterns as strong as expected. One of the reasons of this could be the heterogeneity in vegetation types in the study catchments. Another reason could be that the S_r parameter does not have a very strong physical meaning in boreal regions.

Despite the conceptual character of the climate derived root zone storage capacity, it was expected that it is positively correlated with root density or root biomass; this study is the first to show such a connection exists for spruce and deciduous trees (Figure 5). However, for pine 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, the survival strategies of the trees (e.g., methods to access water or water use efficiency), or the combined effect with other catchment characteristics (e.g., a low density of pine trees in these catchments, thus their influence on the overall transpiration and storage in the catchments or the influence of the drained peatlands in which pine trees often occur). In addition, Figure 5 could also reflect the optimal growing conditions for pine trees: low S_r-values coincide with low transpiration demands and thus likely smaller biomass development. On the other hand, for larger S_r-values the growing conditions for spruce and deciduous tree become better, thus outcompeting the pine trees.

By using a climate derived root zone storage capacity, it is assumed that the S_r developed by the vegetation is in balance with the transpiration demands. Not necessarily one causes the other, but a larger S_r coincides with higher or more variable transpiration demands. When the transpiration demands in boreal areas ~~is~~are higher, it is likely that vegetation has higher potential to develop as well (ie. more leaf cover, larger trees). However, if soil conditions are such that root development is slowed down, but still vegetation survives, it is likely that transpiration demand and thus derived S_r-values are low. Figure 6 shows indeed a positive correlation between S_r and leaf cover or tree height.

4.3 Vegetation types

Although not as strong as for the climate variables and the vegetation characteristics, relations between S_r and vegetation types were found as well, especially for agriculture and pristine peatlands. A lack of strong patterns could, similarly as for the vegetation characteristics, for example be caused by the heterogeneity of the study catchments. The combined effect of different variables is another option that should especially be considered when looking at vegetation types. For example, when looking at the interaction between transpiration demand and vegetation type: does the existence of agriculture or deciduous forest increase transpiration rates and thus derived S_r-values, or are these vegetation types more likely to occur in areas with larger differences between water supply and demand? And linked to this, how large is the influence of the return period to which the vegetation adjusts: agriculture is likely to adjust to a shorter return period than forest. Or what is the role of soil: the used method assumes that soils are not important for the derived S_r, but they probably influence which vegetation will develop, which again influences the transpiration demands. Or how do the development of vegetation type and climate exactly coincide: especially peatland showed to be strongly correlated to climate (Figure 8), but to smaller extends agriculture and deciduous forest as well. To answer these questions, more detailed analysis of specific catchments would be required.

When looking especially at pristine peatlands it can be seen that they have a strong relation with the derived root zone storage capacity. In case of more than 20% pristine peatland cover, S_r does not exceed the earlier found threshold of 115 mm. 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. In the developed peatlands generally the available space for root development is small, due to high groundwater tables and fully saturated soil moisture conditions (e.g. Menberu et al., 2016). 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). Catchments where peatland is drained for forestry show another pattern: the correlation with S_r is lower, but especially the threshold seems to be weaker. The variation between the two groups for the threshold analysis is larger for pristine peatlands than for drained ones (Mann-Whitney U-test, p=0.0008 and p=0.0135 respectively). An effect could be 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 effects on hydrological processes (ie. low flows, peak flows), which could partly be explained by the change in S_r.

Overall, the used data shows a variable relation between S_r-values and both vegetation characteristics and vegetation types and S_r-values in boreal landscapes. This is especially interesting as forestry actions together with shifting vegetation regions are moving towards the north (e.g., Hasper et al., 2016), which may thus result in different outcomes for root zone storage properties. Therefore it would make sense for future catchment scale studies focusing on the effects of changes in land use or climate on hydrological patterns, to take into account possible changes in S_r as well.

4.4 Usefulness of a 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 derived S_r-values with a set of catchment characteristics, which is a first step in exploring the wider application of S_r. The comparison with vegetation characteristics and types showed that the climate derived S_r indeed also has some physical meaning in the study catchments. In addition, the comparison with climate variables showed that the (non-)coincides of snow melt and the onset of potential evaporation has a large influence on the derived S_r-values. Combining these two findings, it can be expected that if the timing of either of them changes, this can have a remarkable effect on the hydrological behaviour of northernboreal catchments can change remarkably. This finding for example may indicate 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 the found threshold occurs in many areas with energy constrained evaporation or that it is mainly linked to the (non-)existence of snow cover.

With this in mind, a climate derived S_r is especially valuable, as it will probably change when the climatic conditions (ie. amount of precipitation, snow-off date) or vegetation properties (ie. transpiration pattern) change. Before S_r-values can be used in this way, more analyses should be carried out to investigate how (quickly) new equilibria are established and whether vegetation does change their survival mechanisms. However, when 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 investigated the relations between a set of catchment and vegetation characteristics and the derived root zone storage capacit~~y~~ies to further understand the possibilities and physical meaning of this parameter. A climate derived S_r was compared with climate variables, vegetation characteristics and vegetation 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 supports the plausibility of the climate-based method. 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 supply and demand 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 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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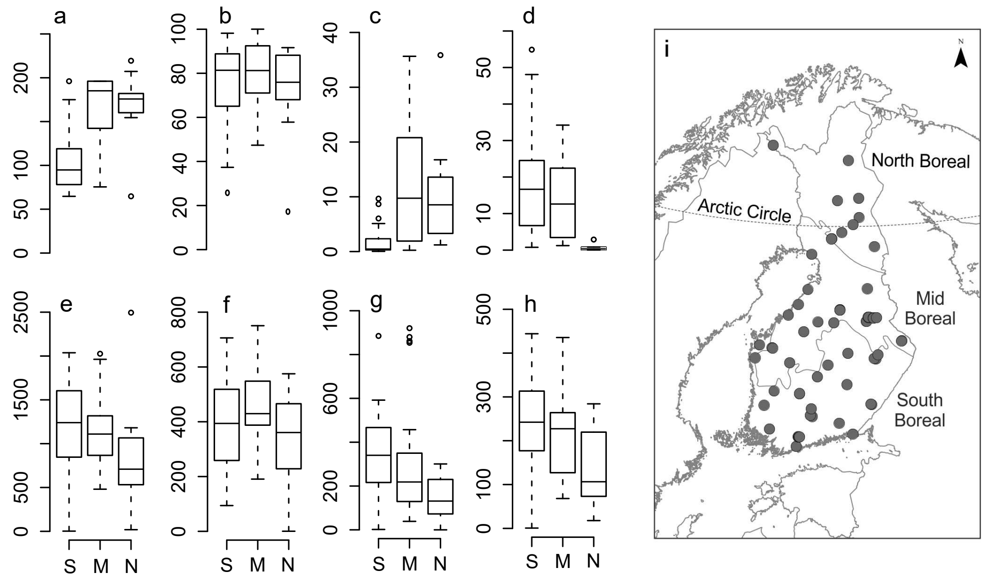

Figure 1. [derived S_r-values were replaced by forest cover]a) Root zone storage capacity (mm), ba) maximum snow water equivalent (S_{SWE}, mm), b) percentage forest (%), c) percentage of pristine peatlands (%), d) percentage of agricultural areas (%), e) total tree root biomass (10 kg/ha), f) pine root 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).

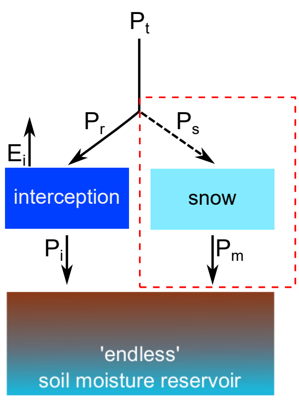

Figure 2. Schematisation of the method to calculate S_r, including snow module; the part in the red square is added for this research, the 'endless' soil moisture reservoir is similarly to the one in de Boer-Euser et al. (2016). The arrow for P_s is dashed as this flux is not actually calculated, but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

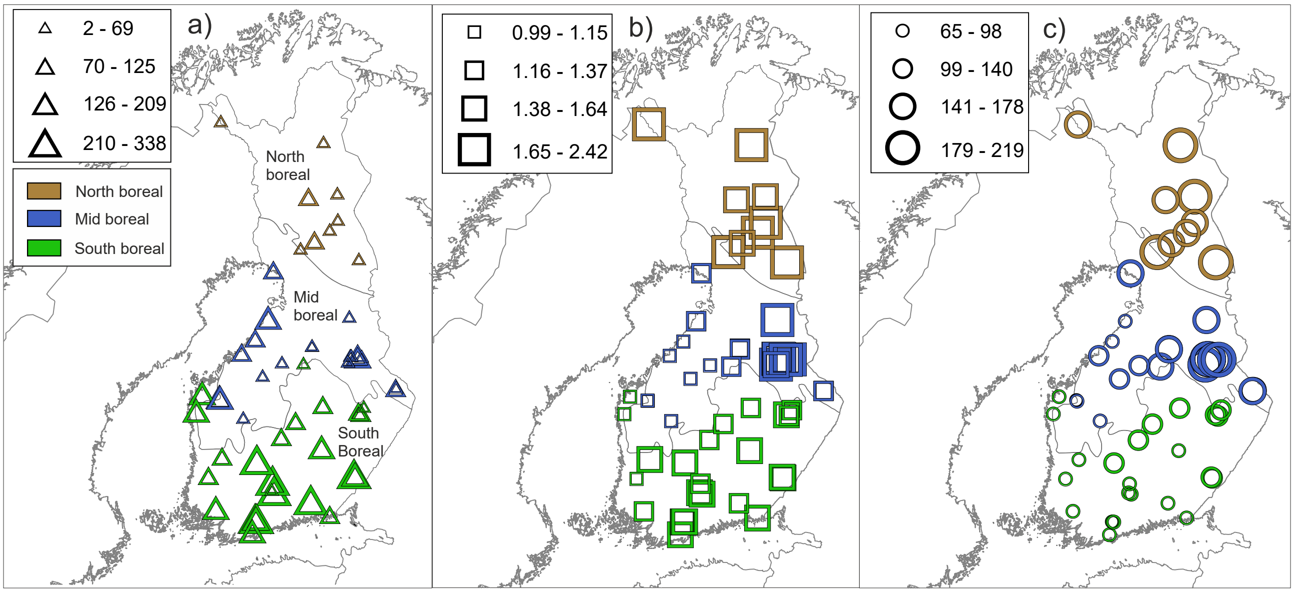

Figure 3. [The colour scheme of this figure was changed: symbols are now coloured instead of the background map]Map with study catchments and a) calculated root zone storage values (S_r, mm), b) ratio of precipitation and potential evaporation, and c) maximum snow water equivalent (S_{SWE}, mm). Different boreal ecoregions (south boreal, mid-boreal and north boreal) are shown in colors of the symbols and ~~subdivision~~boundaries of ecoregions ~~is~~are marked with gray lines.

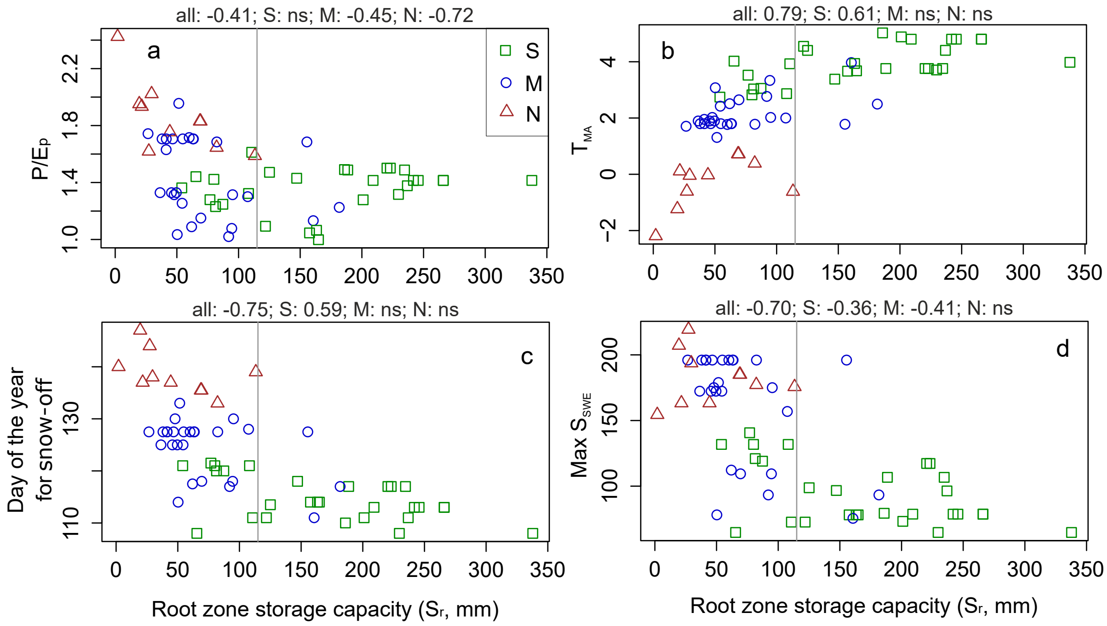

Figure 4. Root zone storage capacities and a) ratio of average precipitation and potential evaporation (P/E_p), b) mean annual temperature (T_{MA}), c) day of the year for snow-off, and d) maximum snow water equivalent (S_{SWE}) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for p<0.05). The line at 115 mm illustrates the discussed threshold.

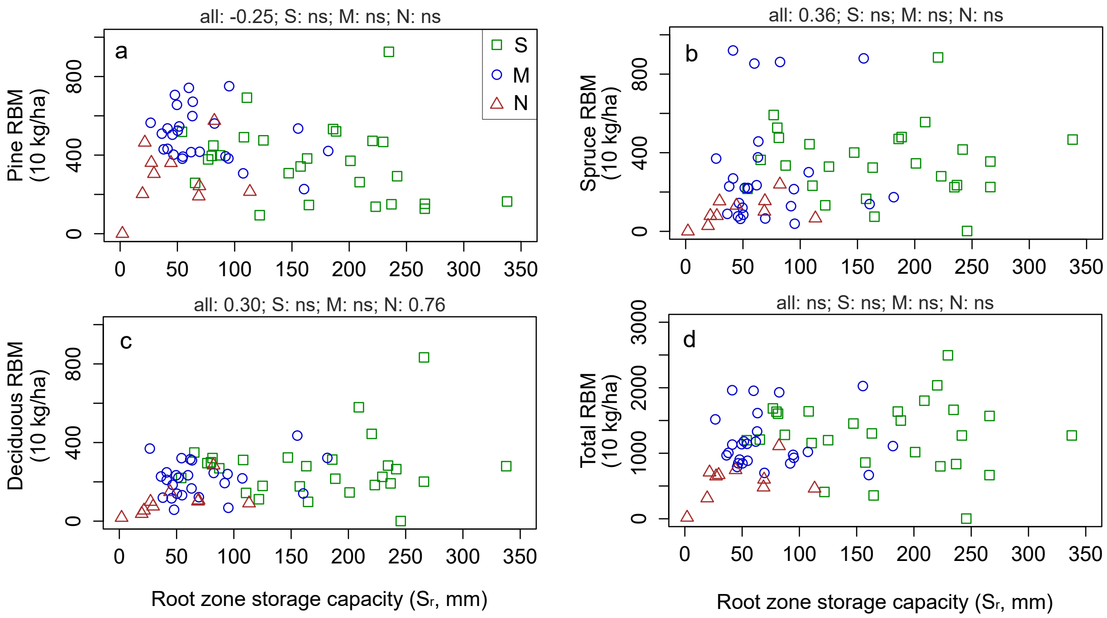

Figure 5. Root zone storage capacities and a) pine root biomass (RBM, 10 kg/ha), b) spruce RBM (10 kg/ha), c) deciduous RBM (10 kg/ha) and d) total RBM (10 kg/ha) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for $p<0.05$).

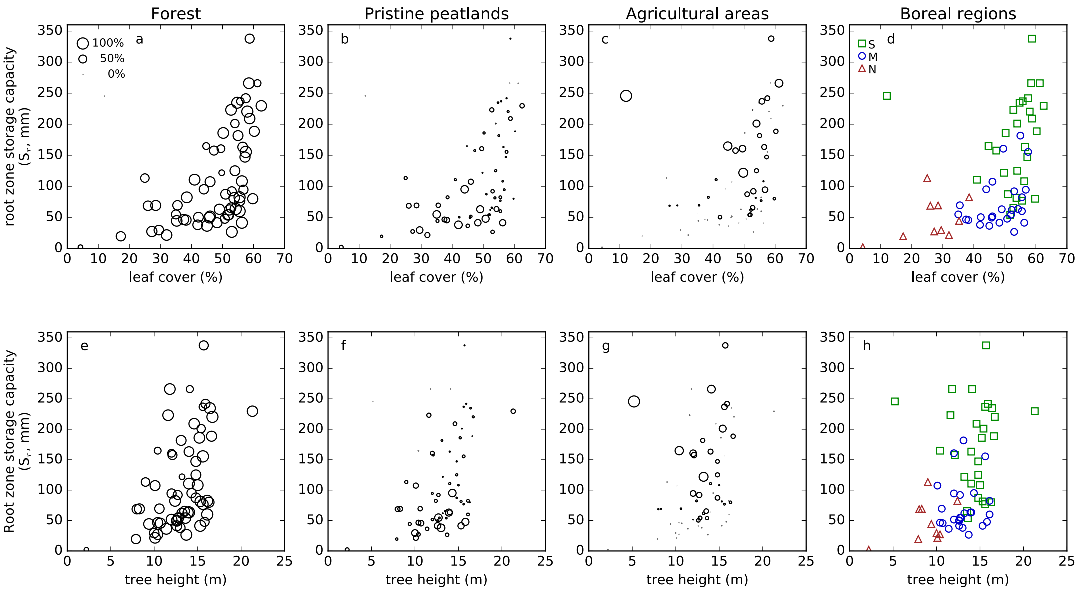

Figure 6. [A legend for the point sizes was added to this figure]Calculated root zone storage capacity versus average leaf cover (top) and tree height (bottom) of four years. Larger circles indicate higher percentage of vegetation type for a&e) forest, b&f) pristine peatlands, c&g) agriculture; d&h) are colour coded by boreal region. S_r has statistically significant Spearman's correlation with leaf cover ($r = 0.33$) and tree height ($r = 0.32$). Different boreal regions did not resulted in statistically significant correlations when considered individually.

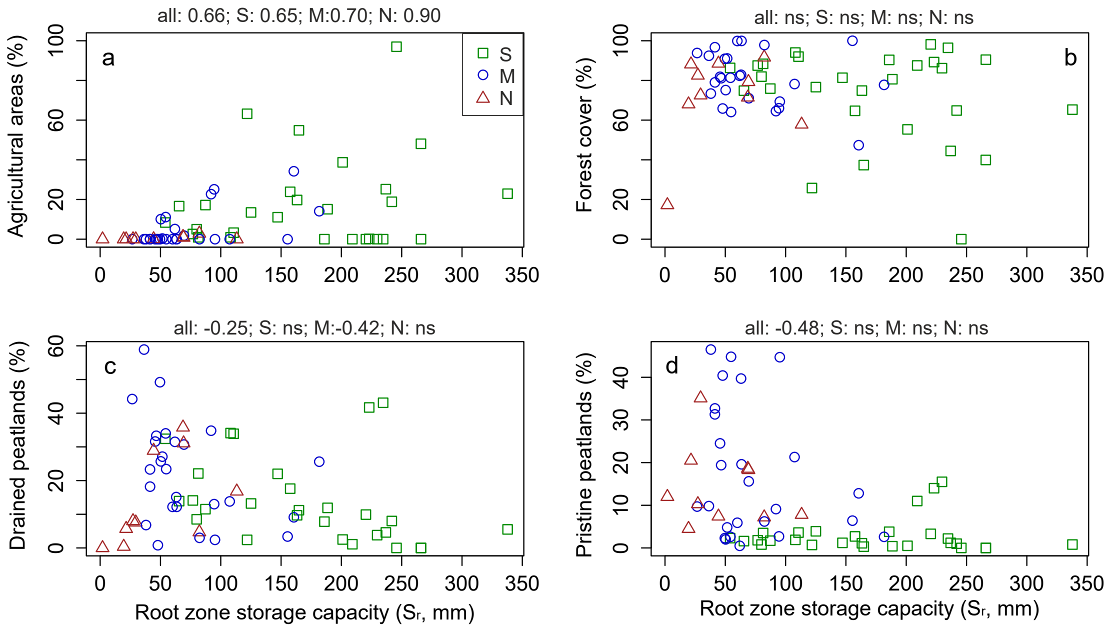

Figure 7. [Catchments in which a vegetation type is not present, are added to the subplots]Root zone storage capacities (S_r, mm) and proportion of a) agricultural areas (%), b) forest cover (%), c) drained peatlands (%) and d) undrained peatlands (%) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for p<0.05). Note that not all vegetation types are present in each catchment, thus the number of catchments per subplot may differ.

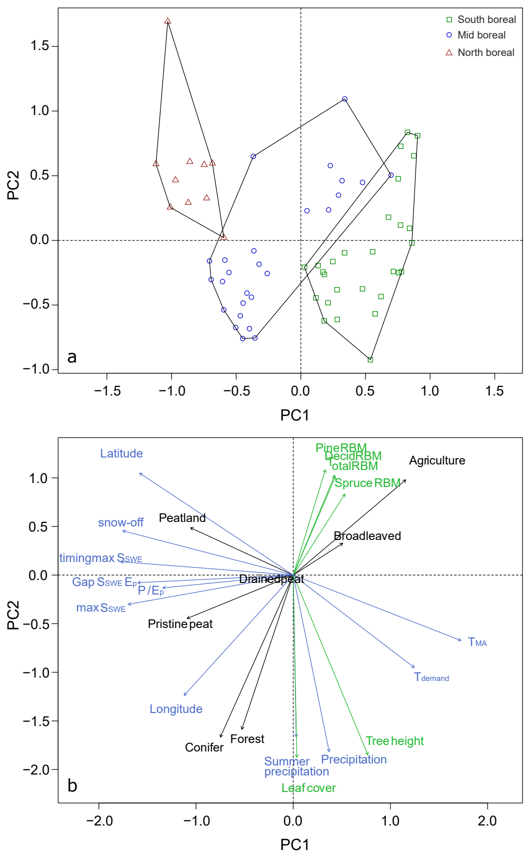

Figure 8. Principal component analysis with the catchment characteristics that are being compared with S_r in the study. a) Catchments plotted on PC1 and PC2, with boreal regions indicated. ~~Note that for readability the axis of the two plots are not the same.~~ b) Catchment characteristics with their loadings on PC1 and PC2; catchment characteristics are divided into three categories: climate (blue), vegetation characteristics (green) and land use types (black). Note that for readability the axis of the two plots are not the same.

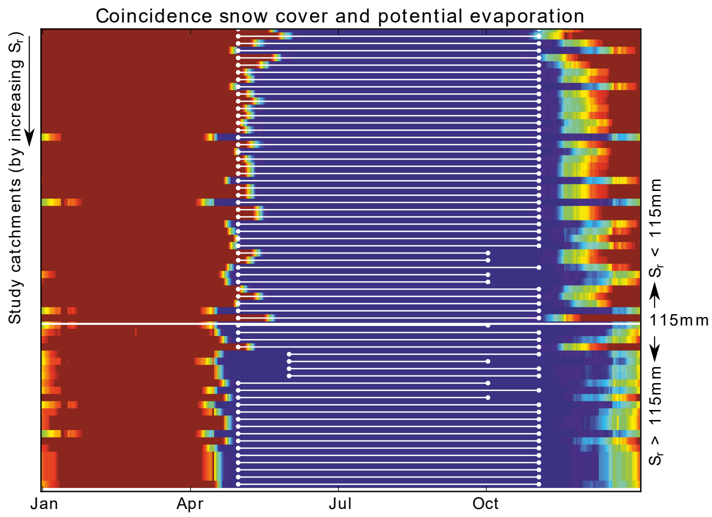

Figure 9. Snow cover is presented by the colour plot (red: S_{SWE} > 15 mm, blue: S_{SWE} = 0). Occurrence of potential evaporation (E_p > 0) is presented by white lines; note that the actual amount of E_p is not presented. Presented data are long term daily averages. Catchments are ordered by increasing S_r-values.

Supplement belonging to "Understanding variability in root zone storage capacity in boreal regions"

by Tanja de Boer-Euser, Leo-Juhani Meriö, Hannu Marttila

1 Background on study catchments

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

Table 1: Vegetation and land use characteristics of study catchments

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broad-leaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
7	Rudbäcken1	1.42	532	470	313	1636	90	53	4	0	8	4	50	152
11	Hovi	0.12	0	2	1	2	0	0	0	97	0	0	12	52
12	Ali-Knuuttila	0.25	127	225	201	666	40	18	6	48	0	0	61	141
13	Yli-Knuuttila	0.07	152	355	833	1569	90	11	29	0	0	0	59	118
14	Teeressuonoja	0.69	262	556	579	1802	88	30	13	0	1	11	59	146
15	Kylmänoja	4.04	293	416	265	1271	65	36	6	19	8	1	58	159
17	Koppelonoja	7.81	164	467	280	1271	65	33	5	23	6	1	59	157
18	Löyttynoja	8.2	259	363	349	1209	75	38	5	17	14	2	53	135
21	Löytäneenoja	5.64	94	132	111	409	26	13	1	63	2	1	50	132
22	Savijoki	15.4	371	346	146	1017	55	37	1	39	3	1	54	154
31	Paunulanpuro	1.5	472	885	444	2037	98	66	1	0	10	3	58	167
32	Siukolanpuro	1.86	138	280	184	800	89	58	2	0	42	14	53	116
33	Katajaluoma	11.2	692	232	144	1155	92	66	0	3	34	4	41	140
41	Niittyjoki	29.7	150	235	192	835	44	24	3	25	5	1	56	156

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
42	Ravijoki	56.9	475	329	179	1199	77	51	4	13	13	4	54	148
43	Latosuonoja	5.34	521	480	216	1499	81	60	2	15	12	0	60	166
44	Huhtisuonoja	5.03	926	225	283	1663	96	80	0	0	43	2	55	164
45	Juonistonoja	13	308	401	324	1454	81	42	5	11	22	1	57	148
51	Kesselinpuro	21.7	491	443	311	1639	94	59	2	1	34	2	56	150
52	Kuokkalanoja	2.67	396	527	300	1634	82	51	6	5	9	1	60	163
53	Mustapuro	11.2	518	216	220	1199	86	55	3	8	32	2	52	136
54	Murtopuro	4.94	565	370	369	1517	94	47	1	0	44	10	53	137
55	Liuhapuro	1.65	536	920	248	1962	97	75	0	0	23	31	56	153
56	Suopuro	1.13	392	219	132	886	64	50	0	0	23	45	35	127
57	Välipuro	0.86	599	376	166	1333	83	75	0	0	15	40	49	139
58	Kivipuro	0.54	672	457	309	1613	100	83	0	0	12	20	54	140
59	Koivupuro	1.18	402	144	185	847	81	53	0	0	33	19	38	104
61	Korpijoki	122	382	220	321	1143	81	43	5	11	34	3	52	128

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-culture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
62	Kohisevanpuro	10.65	449	476	321	1604	88	53	4	1	22	4	54	153
71	Ruunapuro	5.39	399	335	269	1281	76	48	5	17	12	2	51	148
72	Heinäjoki	9.4	378	592	295	1684	88	58	3	3	14	2	56	156
81	Haapajyrä	6.09	146	74	98	356	37	18	2	55	11	0	45	104
82	Kainastonlu-oma	79.2	342	165	177	858	65	35	2	24	18	3	47	121
83	Kaidesluoma	45.5	524	84	140	846	75	54	1	10	26	2	42	126
84	Norrskogsdiket	11.6	227	138	141	667	47	29	1	34	9	13	50	120
85	Sulvanjoki	26.85	383	324	280	1302	75	48	2	20	10	1	57	140
91	Tuuraoja	23.5	394	128	194	844	65	39	1	23	35	9	53	127
92	Tujuoja	20.5	415	235	315	1178	82	48	4	5	32	1	52	132
93	Pahkaoja	23.3	417	65	122	700	71	50	0	2	31	16	36	106
94	Kuikkisenoja	8.05	383	215	240	975	66	36	3	25	13	3	57	120
101	Huopakinoja	19.7	421	174	322	1110	78	40	4	14	26	3	55	131

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
102	Vääräjoki	19.3	305	153	75	670	73	51	0	0	8	35	30	100
103	Myllypuro	9.86	546	221	221	1181	91	61	0	0	27	5	46	120
104	Murronoja	4.38	509	89	227	968	92	57	1	0	59	10	45	114
105	Koppamäenoja	6.15	504	76	116	791	82	52	1	0	32	25	38	107
106	Kaukolanpuro	4.84	656	120	233	1138	91	63	1	0	49	2	46	126
111	Kuusivaaran-puro	27.6	361	131	149	745	89	50	0	0	29	7	35	94
112	Lismanoja	2.77	214	66	91	463	58	43	0	0	17	8	25	90
113	Korintteenoja	6.13	575	239	284	1111	92	75	0	3	5	7	39	124
114	Vähä-Askanjoki	16.4	464	79	55	709	88	67	0	0	6	21	32	101
116	Myllyoja	28.5	362	79	99	649	83	50	1	0	8	10	27	104
117	Iittovuoma	11.6	0	0	18	19	17	0	17	0	0	12	4	22
118	Kirnuoja	6.79	307	301	218	1020	78	25	3	0	14	21	46	101
119	Ylijoki	56.27	191	101	101	480	72	39	1	1	36	19	26	80

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
120	Kotioja	18.11	243	154	106	600	79	48	1	1	31	18	29	83
121	Laanioja	13.62	203	28	38	314	68	57	0	0	0	5	17	79
200	Valkea-Kotinen	0.34	467	1656	226	2495	86	86	0	0	4	16	63	213
201	Iso Hietajärvi	4.64	706	63	58	903	66	58	0	0	1	40	51	158
202	Pieni Hietajärvi	0.67	751	39	68	930	69	58	0	0	2	45	44	143
501	Kauheanpuro	1.76	432	269	210	1132	79	51	1	0	18	33	48	126
502	Korsukorven-puro	0.72	429	229	120	1007	73	60	0	0	7	47	42	130
503	Kangasvaaran-puro	0.56	561	862	245	1930	98	78	2	0	3	6	56	161
504	Kangaslammen-puro	0.3	535	880	436	2026	100	78	0	0	3	6	58	156
505	Porkkasalon-puro	0.72	742	854	233	1954	100	90	0	0	12	6	56	161

Table 2: Climate characteristics of study catchments

ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual SWE (mm)	P/E_P (-)	Snow-off (Julian date)
7	Rudbäcken1	5	682	79	1.49	110
11	Hovi	4.8	652	79	1.42	113
12	Ali-Knuuttila	4.8	652	79	1.42	113
13	Yli-Knuuttila	4.8	652	79	1.42	113
14	Teeressuonoja	4.8	652	79	1.42	113
15	Kylmänoja	4.8	652	79	1.42	113
17	Koppelonoja	4	616	65	1.41	108
18	Löyttynoja	4	614	65	1.44	108
21	Löytäneenoja	4.5	566	73	1.09	111
22	Savijoki	4.9	664	73	1.28	111
31	Paunulanpuro	3.8	624	117	1.5	117
32	Siukolanpuro	3.8	624	117	1.5	117
33	Katajaluoma	3.9	678	73	1.61	111
41	Niittyjoki	4.4	646	96	1.38	111
42	Ravijoki	4.4	695	99	1.47	113.5
43	Latosuonoja	3.8	623	107	1.49	117
44	Huhtisuonoja	3.8	623	107	1.49	117
45	Juonistonoja	3.4	584	97	1.43	118
51	Kesselinpuro	2.9	605	132	1.32	121
52	Kuokkalanoja	2.8	645	132	1.42	121

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ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
53	Mustapuro	2.7	620	132	1.36	121
54	Murtopuro	1.7	658	196	1.74	127.5
55	Liuhapuro	2	624	196	1.63	127.5
56	Suopuro	1.8	642	196	1.71	127.5
57	Välipuro	1.8	642	196	1.71	127.5
58	Kivipuro	1.8	642	196	1.71	127.5
59	Koivupuro	1.8	642	196	1.71	127.5
61	Korpijoki	2.4	574	172	1.25	125
62	Kohisevanpuro	3	593	121	1.23	120
71	Ruunapuro	3.1	605	119	1.25	120
72	Heinäjoki	3.5	659	141	1.28	121.5
81	Haapajyrä	3.7	533	78	1	114
82	Kainastonluoma	3.7	547	78	1.05	114
83	Kaidesluoma	3.1	545	78	1.03	114
84	Norrskogsdiket	4	572	75	1.13	111
85	Sulvanjoki	3.9	535	78	1.06	114
91	Tuuraoja	2.8	478	93	1.02	117
92	Tujuoja	2.5	533	112	1.09	117.5
93	Pahkaoja	2.6	575	109	1.15	118
94	Kuikkisenoja	3.3	512	109	1.08	118
101	Huopakinoja	2.5	514	93	1.23	117

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ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
102	Vääräjoki	0	581	194	2.02	138
103	Myllypuro	1.3	600	179	1.96	133
104	Murronoja	1.9	607	172	1.33	125
105	Koppamäenoja	1.9	607	172	1.33	125
106	Kaukolanpuro	1.9	607	172	1.33	125
111	Kuusivaaranpuro	0	498	163	1.76	137
112	Lismanoja	-0.6	541	176	1.59	139
113	Korintteenoja	0.4	552	177	1.65	133
114	Vähä-Askanjoki	0.1	546	163	1.93	137
116	Myllyoja	-0.6	550	219	1.62	144
117	Iittovuoma	-2.2	434	154	2.42	140
118	Kirnuoja	2	494	157	1.3	128
119	Ylijoki	0.7	614	185	1.83	135.5
120	Kotioja	0.7	614	185	1.83	135.5
121	Laanioja	-1.2	541	207	1.95	147
200	Valkea-Kotinen	3.7	632	65	1.32	108
201	Iso Hietajärvi	2	652	175	1.31	130
202	Pieni Hietajärvi	2	652	175	1.31	130
501	Kauheanpuro	1.8	642	196	1.71	127.5
502	Korsukorvenpuro	1.8	642	196	1.71	127.5
503	Kangasvaaranpuro	1.8	640	196	1.68	127.5

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ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
504	Kangaslammenpuro	1.8	640	196	1.68	127.5
505	Porkkasalonpuro	1.8	653	196	1.72	127.5

2 Background on correlations between catchment characteristics

2.1 Principal component analysis

Table 3 shows the explained variance of the first two principal components, together with the loadings of all used catchment characteristics on these two principal components.

2.2 Correlation matrix

Figure 1 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 different land covers (except for drained peatlands) also show a significant correlation with the climate variables.

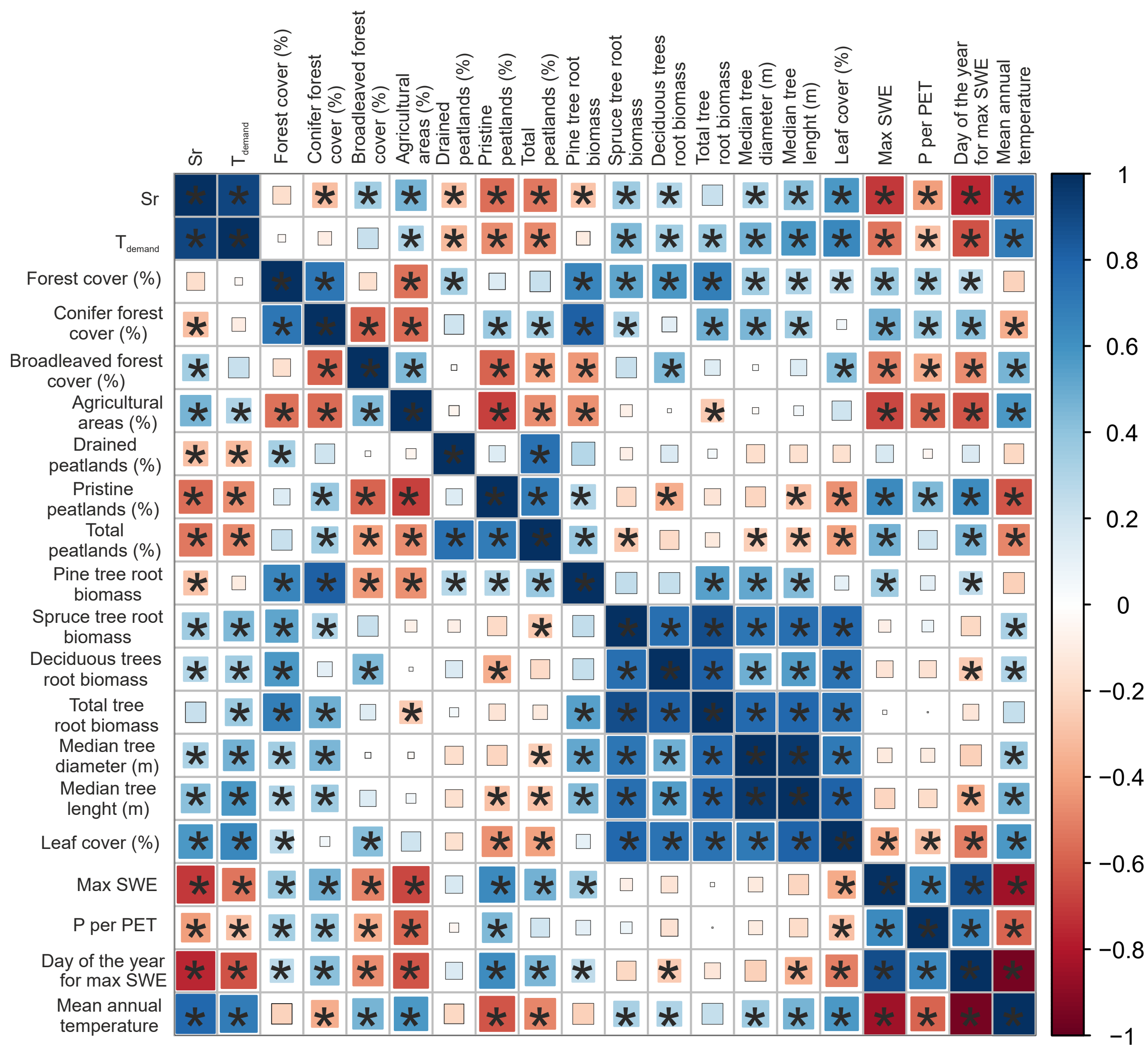

Figure 1: Correlation matrix for calculated root zone storage capacity (20 year return period), calculated transpiration demands (used in the S_r calculation) and catchment characteristics. The sizes of the boxes indicate the p-values; the asterisks indicates a significant correlation (p<0.05).

Table 3: [This table was added]Summary of principal component analysis (PCA). The highest loads for each characteristic are shown in bold.

	PC1	PC2
Eigenvalue	8.20	4.68
% Explained	34	20
Cumulative % explained	34	54
Forest	-0.364	**-0.825**
Conifer	-0.516	**-0.866**
Broadleaved	**0.350**	0.169
Peatland	**-0.727**	0.253
Agriculture	**0.796**	0.509
Precipitation	0.254	**-0.944**
Summer precipitation	0.021	**-0.865**
max S_{SWE}	**-1.168**	-0.156
P/E_p	**-0.923**	-0.068
Longitude	**-0.771**	-0.643
Latitude	**-1.086**	0.544
Leaf cover	0.025	**-0.974**
Pine RBM	0.227	**0.563**
Spruce RBM	0.365	**0.433**
Decidious RBM	0.294	**0.534**
Total RBM	0.298	**0.525**
Tree height	0.528	**-0.961**
Drained peat	**-0.198**	-0.029
Pristine peat	**-0.751**	-0.232
Timing max S_{SWE}	**-1.221**	0.071
snow-off	**-1.206**	0.237
mean annual temperature	**1.186**	-0.349
Tdemand	**0.857**	-0.495
Gap S_{SWE} E_p	**-1.100**	-0.041