Authors’ response to Referees comments

Black text: Referee comment

Blue text: Authors’ response

To make this final response easy to follow and clear, we used our previously published responses which we adjusted accordingly to what we exactly changed in the revised version.

Response to the anonymous Referee #1

We thank the reviewer for the valuable comments and suggestions to improve our contribution. We provide point-by-point reply below.

This paper investigates the role of snow (and rain) on streamflow across 59 Czech catchments. The objectives of the study are: to quantify how snow storages affect spring and summer runoff and to quantify how much runoff snowmelt in generates compared to rainfall. The study uses data of 50 catchments and simulations using the HBV model. They show the following results: 1. Snow runoff fractions exceed snowfall fractions (Fig 3), from which they conclude snow produces more runoff than rain. 2. How much runoff occurs in particular months varies between snow rich and snow poor years (Fig 4), with overall more runoff in snow rich years. 3. Several streamflow signatures vary between snow rich and snow poor years (Fig 5). 4. Summer base flow depends on both SWE and summer P (Fig 6+7) 5. That also in models annual and summer runoff strongly depend on the snow fraction (Fig 8).

These results are generally useful for the HESS’ readership, as they address the important issue of how snow (and its anticipated future changes) affect river flow. However, before I can recommend publication of this article I think several things need to be addressed first:

- This HBV results suggest that snow produces runoff differently than rain. However, HBV treats snowmelt and rainfall largely similarly. This seems counterintuitive (or a paradox). It needs to become clearer in the modeling results how snowmelt is different than rain that leads to these runoff differences. Otherwise, I am not sure what we really learn from the presented results.

Thank you for this valuable comment. The changes in runoff due to snowfall/rain transition as simulated by modelling experiments (Fig. 8) pointed at two different aspects; 1) changes in annual water balance and 2) changes in seasonal runoff distribution. The first aspect was shown in Fig 8a and, in the model, was caused by lower actual evapotranspiration (AET) for higher snowfall fractions due to more days with snow cover (AET is calculated only for days with no snow cover on the ground in the model). We are aware that this particular result is influenced by the model structure which describes the whole rainfall-runoff process in a simplified way and thus the real catchment behaviour might not be captured correctly.

The second aspect, changes in seasonal distribution, was caused mainly by lower snow accumulation for lower snowfall fractions (more rain than snowfall) and by earlier snowmelt. This widely influenced the timing of groundwater recharge and thus spring and summer streamflow, low flows and deficit volumes (Fig. 8b-d). This second aspect is, in our opinion, more important (although expected) since it widely influences the water availability during the warm period when the water demand is generally higher (for vegetation growth, agriculture, hydropower etc.).

We provided a better explanation in the abstract and introduction (better justification for knowledge gaps, L 10-11 and 81-82) and in discussion Section 4.4 (several places in the text between L 475-499). Some more information regarding the model structure and parameter uncertainty was added to Section 4.1 (L 375-385 of the revised version).

- The results listed above as 1-4 have all be shown before or are mostly trivial. There might be value in showing this again for the study catchments, but then I think the paper should better explain what we learn about the hydrology of these places, rather than largely use them as data for making some general statements.

We agree that most of the findings are not surprising as they mostly support our existing qualitative knowledge of how snow contributes to spring and summer runoff. However, we believe that the findings are still important even if they do not change our process understanding, and the quantification is a valuable and novel contribution. Besides, we were concentrated on a non-alpine (outside the Alps) region of Central Europe where there is only a little bit of published information on how ongoing changes in snow storages and snow/rain distribution at different elevations affect seasonal distribution of runoff. This is specifically important for identification of regions which might become more vulnerable to drought occurrence in the future. We also benefit from modelling approach enabling us to simulate both snow and rain runoff components and thus track the snow and rain signal in runoff. We believe that the fact that our focus was on the interplay of different rainfall-runoff components goes beyond what has been done before and thus it might bring some new insight into this topic.

Nevertheless, we are aware that our results are limited to the specific region and may not be easily generalized. Therefore, it was our intention to write the text in this respect. However, maybe, this was not always clear from our formulations. Therefore, we went through the text again to make it clearer, to better highlight the novelty and to put more emphasis on regional consequences of our results. More specifically, we added several statements regarding regional differences between catchments to different parts of the text in the results (text related to Fig. 7, L 289-306) and mainly discussion Section 4.3 (L 435-445 of the revised version). With this, we wanted to put more emphasis on regional aspects of our results. Nevertheless, more detailed investigation of differences between catchments and the potential influence of basin attributes on runoff generation has not been done in this study and needs to be further investigated (as mentioned in Section 4.2).

Additionally, we also tried to avoid drawing general conclusions since we are aware that our results should be related just to our study area or to an area with similar geography and climate. Therefore, we made minor edits at different places of the text in this respect.

- All results of groundwater recharge rely on the model output of an unvalidated flux (since no GW data are used). How do we have confidence they reflect actual groundwater recharge behaviours?

It is true that our results are not based on direct measurements of all individual runoff components since such measurements were not available for all analysed components. Therefore, we calibrated a model to simulate those components of the water cycle, for which observational data were not available. The HBV model, which was used in our study, is, despite its simplicity (and thus limiting ability to represent rainfall-runoff process in a fully physical way), widely used and accepted by the scientific community, especially for impact modelling at a catchment scale. To better address the model uncertainty, we used an integrated multi-criteria approach to calibrate and validate the model using three objective functions reflecting both observed streamflow and SWE. The model allows using also groundwater (GW) data for calibration, but these data are not easily available for all study catchments. Besides, the density of the measuring network does not allow us to find the GW stations (either boreholes or springs as a proxy) which would sufficiently represent the whole catchment since the spatial variability in GW storages in a catchment is very large due to the variability in geology and soils. In contrast, the streamflow used to calibrate the model represents the integrated output from the whole catchment, and also the observed SWE data usually represents the catchment snow storage well enough (at least at a specific elevation zone). Therefore, it is questionable to which degree the use of the GW data for model calibration would result in more accurate simulations.

Additionally, we were concentrated on relative differences (year-to-year variations) between groundwater fluxes in individual catchments rather than on absolute values. Some studies also showed (Staudinger et al. 2017) that catchment storage calculated using different methods (water balance calculations, recession curve analysis, HBV modelling) are, in general, comparable and correlated, although the quantitative estimates may differ. Therefore, we believe that using HBV simulations for assessing the relative inter-annual differences in GW storage was an acceptable approach even when GW data were not used for model calibration.

We included the above explanation into discussion Section 4.1 (L 351-361) to better describe all uncertainties and limitations of using such a model for this topic.

- The paper contains a lot of unclear statements or language that if (interpreted as written) is wrong. I made a list of suggestions below, but this list is far from comprehensive. Please check the paper another time critically. This is really important because for too many statements it remains unclear what the authors claim to be true, and thereby makes it even impossible to review

Thank you for the comment. The text was corrected by a native speaker (hydrologist) and we carefully went through the text again to correct all language errors (including those mentioned below).

Detailed comments

L9: add the word “often” (or something similar), otherwise this general statement is false.

Added.

L11: (and in winter runoff). Not necessary to state, but maybe not bad to mention.

Changed to “winter to summer runoff”.

L14: model output, not model performance.

Changed.

L15: the simulations are not “hypothetical” as they have been performed. I the paper intends to say something like “Hypothetical scenarios were modelled”

Changed to “hypothetical scenarios”.

L19-20: “This was documented by [: : :] from snow to rain” This does not seem to be a logical statement. Maybe change the verb “documented”?

“Documented” replaced by “demonstrated”,

L22: would “reduced” be more specific than “affected” and therefore more informative?

The word “affected” was used in the original manuscript because the baseflow was not reduced in all catchments (as explained in the next sentence). Therefore, we prefer to keep the sentence as is to avoid confusions, although it is less informative.

L29: “largely affects” seems a bit odd. Maybe “often affects” or “can affect”.

Changed to “significantly” since the snow impact on runoff seasonality is really important and often substantial.

L30: “tend to occur” not “occurs”.

Changed.

L32: “to increase [: : :] climate changes“. Why mention “precipitation”? And reword “to increase in air temperature” to “to increasing air temperatures”. (And probably make “climate changes” singular).

Changed.

L34: “during winter” may be an unnecessary (and sometimes wrong) specification here. In many mountain areas the shift from snow towards rain will be biggest in spring and fall (when temperatures are often near 0) compared to winter (when temperatures are generally below zero even when it gets a bit warmer)

We removed “during winter”.

L34: “a rate of”? I do not think this makes sense here. Please check what is intended to be said here.

We changed “rate” to “proportion”. The whole part is a definition of “snowfall fraction” (which is firstly used here) to avoid confusion about this term.

L35: would “reduced” be more specific than “affected” and therefore more informative?

Changed.

L37-38: I understand why you say “On the contrary” but this only makes sense by having the reader guess that this has an opposite effect on total streamflow generated (which you don’t say, nor make it clear that this is what you’re thinking about). Therefore I would try to reword this a little.

We removed the sentence since the mentioned information has no link to the previous information and, thus, we think it is redundant in this context.

L39-40: “Changes in [: : :] and occurs earlier”. Or “Reduced snow accumulation, and earlier and slower snowmelt cause earlier and less groundwater recharge (Beaulieu et al., 2012; Foster et al., 2016).”

Changed, thank you for the suggestion.

L41: to “lower elevations” (make plural)

Changed.

L44-45: “Higher snowpack generates higher groundwater flow driven by snowmelt rates and thus contributes more to streamflow 45 (Barnhart et al., 2016).” Does not seem to be a logical statement. Do you mean something like “Higher snowpack disproportionally feed groundwater leading to more to streamflow (Barnhart et al., 2016)”?

Changed, thank you for the suggestion.

L54: “were” seems redundant.

Removed.

L57: Thus “using” not “uses”

Corrected.

L96: Consider removing “the” at the start of the sentence.

The sentence was reworded.

L110-111: “For this, we used a bucket-type HBV model (Lindström et al., 1997) in its implementation, called HBV-light (Seibert and Vis, 2012)” This sentence is clear, but I would recommend to rephrase it. (E.g. remove ‘in its implementation”)

We wanted to mention that we used an HBV-light version of the model, which is the specific software implementation of the original HBV model. We slightly reworded the sentence.

L121: “Different weights were tested to achieve the best possible performance of the model” This seems somewhat vague and arbitrary. What made you choose the particular weight in the end (i.e. what made them the “best”)?

Although we tested different weights, it is true that we did not use any consistent approach to find the best values of these weights. The testing was done just based on our experience with the model and based on the literature. Therefore, it is true that the choice was rather arbitrary, although it reflected the main purpose of the model use (accurate simulation of both high and low flows, water balance and snow storages). We reformulated the respective part to be clearer (L 129-131).

L133-134: “The similar procedures for model set-up and calibration was also used earlier in (Jenicek et al., 2018), although in different region.” Fix the language of this sentence. For example by: something like “This procedure for model set-up and calibration was also used in Jenicek et al. (2018), although for different region”.

Changed, thank you for the suggestion.

L137: the simulations are not “hypothetical” as they have been performed. I the paper intends to say something like “Hypothetical scenarios were modelled”

Changed.

L182: I am unsure what “simulated correctly” would really mean here. Do you mean “accurately simulated”?

Yes, we mean “accurately simulated”. We changed it.

L192-200: It is unclear to me to what extent these results originate from snow being more effective in producing runoff than rain or whether this is because of the seasonal timing of precipitation (independent whether it’s snow or rain).

We don’t know whether we correctly understand this comment. The results here (Fig. 3) were analysed for individual hydrological years (1 Nov – 31 Oct) and thus any deviations from 1:1 line (Fig. 3a) should indicate, in our opinion, differences in annual water balance rather than differences in seasonal runoff distribution. We added more explanation to the revised version by emphasizing that the figure shows annual (not seasonal) water balances. Additionally, we reformulated the figure caption to be clearer.

L435: “This particular result proves that snow is more effective in generating catchment runoff compared to liquid precipitation” seems like an overly strong statement. Tone down the word “prove” and choose something like “indicates” or “suggests”.

We agree, changed to “suggests”.

L454-456: “. An understanding of potential model artifacts might be important : : :” is very vague. Can it be made more specific?

This conclusion referred to the issue about how the model structure could influence results discussed in Section 4.1. After consideration we decided to remove this sentence from concluding Section 5 since it is not much informative. Nevertheless, we significantly enriched related discussion Section 4.1 to provide the reader with more specific information about potential effects of individual values of model parameters on results.

Response to the anonymous Referee #2

We thank the reviewer for the valuable comments and suggestions to improve our contribution. We provide point-by-point reply below.

The paper presents how snow processes influence runoff generation in mountainous catchments in Czechia. The presented results are not novel, and similar things have been shown across different regions. However, the manuscript could still be a valuable contribution for the readership of HESS. The overall structure of the manuscript is quite clear, but inconsistent language makes the paper sometimes hard to follow, especially throughout the introduction and discussion. Below I suggest some changes that should be considered prior to publication.

At this point, I am not convinced by the conclusion that "snow is more effective in generating catchment runoff compared to liquid precipitation". First of all, it is not clear what I actually see in Figure 3: Did you plot the mean of both groups (snow rich and snow poor) for every catchment? Please add some information to make this clearer.

Thank you for the comment. As you correctly assume, individual points in Figure 3 represent mean snowfall fractions and snow runoff fractions for snow-poor and snow-rich years for individual catchments. The snow-rich years were defined as years with annual SWE_{max} above the third quartile of the study period (1980-2014), while the snow-poor years represent years with annual SWE_{max} below the first quartile of the study period. Therefore, each point represents a mean calculated from 8-9 annual values derived from ~35-year-long time series.

By Figure 3, we wanted to demonstrate to what degree the snowfall is important for runoff generation compared to rainfall in our study catchments. This was also assessed by runoff coefficients calculated separately for snowfall to snowmelt runoff and rain to rainfall runoff (values are not shown in the paper, but they are discussed in Section 3.2). The higher runoff fraction for snow-generated runoff is caused mainly by lower actual evapotranspiration during winter (see also our response to Referee 1). Additionally, in modelling experiments we showed that the transition of snowfall to rain caused changes in 1) annual water balance and 2) seasonal runoff distribution, affecting groundwater recharge and summer low flows (Fig. 8).

The above explanation was used to clarify the text at several places, specifically 1) we added a bit more explanation to methodological Section 2.4 (regarding snow runoff calculation in HBV, L 170-172), 2) to results Section 3.2 (better description of Figure 3, including rewording of the figure caption, L 205-210) and 3) we added more explanation to the related part of discussion Section 4.4 (consequences for seasonal runoff distribution and water availability, several edits within lines 475-499).

Second, I'd like to see the same calculations (Figure 3) with the absolute values for total snowmelt runoff and total snowfall precipitation as 26% (on average) of total runoff might still be less than 20% (on average) precipitation.

It is true that, in absolute values, snowfall represents a higher water volume than runoff from snow. By definition of the "effect tracking" algorithm in HBV (as described in Section 2.4), the source of the input water (precipitation) can be changed only by refreezing (from rain to snow), but this process is rather negligible in absolute terms. Therefore, snowfall will be always higher than snowmelt runoff over the defined longer period (losses from evapotranspiration will likely be always higher than changes of water source from rain to snow due to refreezing). Nevertheless, in few catchments it happened that few hydrological years showed higher snowmelt runoff than snowfall in that year since part of this snowmelt contribution came from the previous year (probably thanks to a long catchment storage). The mentioned effect is certainly worth investigating further, but it goes beyond the scope of the current manuscript.

We added more text regarding this issue to the methods (Section 2.4) to better explain the partitioning of the rain and snowmelt runoff. Additionally, the above explanation was added to discussion Section 4.2 (L 395-399) to provide the reader with thorough explanation and interpretation. We also created a new figure according to your suggestion which shows absolute snowfall and snowmelt runoff values, but, finally, we decided not to include it since we thought it would not provide any new information. However, we are open to include it if requested.

Also the increasing trend with elevation in my opinion is not visible in the results. There needs to be further analysis (maybe cluster in elevation groups) to convince readers. I understand that some of these results are also supported by the HBV modelling. However, you need to more explicitly convince readers that snow vs. rainfall processes can be well separated in the current modelling setup.

You are right that we cannot draw a direct conclusion regarding the effect of elevation. The increase in the difference between snowfall fraction and snow runoff fraction is statistically significant for catchments with higher snowfall fraction (see Fig. 3b) rather than higher elevation. In general, the dependence on elevation is not directly evident from the results, although some other results in our study (e.g. Fig. 5) indicated the relation with snowfall fraction, which generally increases with mean catchment elevation. Although the snowfall fraction significantly increases with mean catchment elevation in our study catchments (Pearson correlation coefficient is 0.53, p value<0.001), the correlation coefficient might be influenced by the fact that mean catchment elevation cannot describe the hypsography of individual catchments.

We clarified it better in the revised version of the manuscript by 1) adding the above explanation to discussion Section 4.3 (L 435-444) and by 2) toning down the interpretation regarding the effect of elevation, and highlighted the effect of snowfall fraction instead (see Fig. 3b and Fig. 5) wherever relevant in the Introduction, Results and Discussion sections.

A better characterization of the catchments (i.e., the runoff regimes, precipitation and runoff seasonality) is warranted. This will help to better emphasize why these results are valuable and why it might be useful to show the results for these specific study regions. To people who are not familiar with topography and hydroclimatology of Czechia it would be very helpful to have more "background" information on the study catchments. Please add a table with information on mean, max, min size, elevation, precipitation, temperature, discharge,: : :

Thank you for the suggestion. We added a new table (Table 1 in the revised version) showing the main catchment attributes and meteorological characteristics. We agree that this information might be useful for readers. Similar comment was also made by Referee 1.

Similarly to the comment made by Referee 1 and based on one of your comment below, we added several statements regarding regional differences between catchments to various parts of the text describing the results (text related to Fig. 7; L 289-306) and mainly to discussion Section 4.3 (L 435-447). With this, we wanted to put more emphasis on regional aspects of our results. Nevertheless, more detailed investigation into differences between catchments and the potential influence of basin attributes on runoff generation has not been conducted in this study and remains to be carried out in the future (as mentioned in Section 4.2).

Additionally, we also tried to avoid drawing general conclusions since we were aware that our results should be related just to our study area or to an area with similar geography and climate. Therefore, we made minor edits at different places of the text in this respect.

What are the main differences between the regions, and the four sample catchments? This is important to interpret the results afterwards (some of them are shown based on the different sample catchments). If I interpret the DEM correctly your highest peak is only 1602 m a.s.l., some of the catchments are far below 1000m in peak elevation, do they even have snowfall / accumulation every year? I find it difficult that, in the discussion section, you interpret the results based on the different regions, however they are not well characterized.

The four selected catchments represent different geographical regions, geology and elevations. We added more detailed information to the text (L 231-233). Individual catchments were also described through their attributes and climate characteristics in newly added Table 1.

Although the mean catchment elevation ranges only from 491 to 1297 m a.s.l, all catchments have the seasonal snowpack every year (mean SWE_{max} for individual catchments ranges from 35 mm for lowest catchments to 664 mm for highest catchments). This information was added to Section 2.1 (L 101-104).

Detailed comments

line 98 you claim that the selection criterion is timeseries >35 years however in line 104 /105 you write that three catchments do have less data

It is correct that three catchments have shorter time series (by one or two years compared to the rest of catchments). We are aware that it may bring some inhomogeneity into results, but since the shortening is only one or two years, we decided to include those relatively snow-rich catchments in the analysis. We slightly reformulated the respective sentence (L 98-99).

line 125 although I tend to believe that annual precipitation, peak SWE did not change significantly it would be great to see this (maybe in a table in the supplementary)

Thank you for the comment. The mean SWE_{max} was 141 mm for the calibration period and 140 mm for the validation period; annual precipitation was 1104 mm for the calibration period and 1143 mm for the validation period. We added those numbers to the respective paragraph in the methods (Section 2.2, L 135-138) next to the information about the increase in mean annual temperature by 0.7°C between both periods.

line 155 what is the range of threshold temperature throughout the catchments?

Threshold temperatures for individual catchments calculated from median simulations (100 parameter sets) range from -1.58°C to 1.13°C. We added this information to the respective part of methodological Section 2.4.

Section 3.1 is not overly informative, in my opinion it can be moved to the supplement.

We think that showing the results for calibration and validation might be important for many readers to assess the overall ability of the model to simulate the individual components of the water cycle. Putting this part into the supplement would probably cause a lot of readers to simply miss the information especially if this would be the only supplementary information. Therefore, we prefer to keep this sub-section in the main text.

Figure 4 (and Figure 8): catchments are sorted by "mean" elevation, also add an arrow and write elevation next to y axis, and at least give starting and end value (115m a.s.l. to 1602m a.s.l.)

We agree, we added the elevation ranges as y-axis labels to Fig. 4 and Fig. 8. We added "mean catchment elevation" to the figure captions.

Figure 4 (and Figure 6): make it clear, that you show the results for four specific catchments maybe by using the catchment names as headlines for the subpanels)

We agree, adding the catchments names to individual panels may increase the readability of both figures. We added the names to Fig. 4 and Fig. 6.

Figure 5 and Figure 7: make sure that you use different color coding, as you show different things (in Figure 5 Sf and in Figure 5 the regions)

Thank you for the suggestion. We changed the colour coding in Fig. 7 to avoid confusions with Fig. 5.

Figure 5 please mention the abbreviations (as in the axis titles) also in the figure caption

We agree, we added the abbreviations to the figure caption.

Figure 7 is a bit confusing: In panel (a), do you show a point for each catchment where x is the mean of baseflow from all years having below average summer precipitation and y is the mean of baseflow from all years having below average SWEmax? If that is what I see in Figure 7a, than 58 out of 59 catchments have below average summer baseflow when they experience below average summer precipitation. However, only 40 out of 59 catchments had lower summer baseflow when having lower SWE, which is not supporting your conclusion on the importance of SWE. Please revise this figure (and its caption) to make it clear what is shown.

By Figure 7, we wanted to show the relative importance of annual SWE_{max} and summer precipitation for summer baseflow. For example, Figure 7a shows the median summer baseflow relative anomalies for years with below-average summer precipitation (x-axis) compared to the median of summer baseflow relative anomalies for years with below-average SWE_{max} (y-axis). From Figure 7a it is clear that summer precipitation is more important for summer baseflow than SWE_{max} (as we mentioned in line 277 of the original manuscript; L 296-297 of the revised version). Nevertheless, Figure 7b indicated that for the majority of catchments, the summer baseflow for years with below-average summer precipitation increased when there was simultaneously above-average SWE_{max}. Moreover, some of the catchments showed even positive summer baseflow anomalies for above-average SWE_{max} despite the negative anomaly of summer precipitation.

We are not saying that snow storages play a major role in generating summer baseflow, but results indicated that SWE is an important additional driver. An important implication for the future climate is that the summer baseflow might be lower because of lower snow storages even when summer precipitation would not change.

We agree that our explanation may not be fully clear. Therefore, we reformulated the respective part of results Section 3.2 (L 289-306), and we added more discussion to Section 4.3 (L 445-449).

In Figure 8 please consider using the same scale for the color bars to make the panels comparable.

Thank you for the suggestion. We tested unified scales already during the manuscript preparation and decided in favour of different scales since the scales are of different magnitude. This is especially valid for panel (d) where the magnitude is of different order compared to other panels. Therefore, we prefer to keep the respective figure as is (besides the modifications described earlier).

Discussion: You mention data errors in the headline of 4.1 but you did not discuss them.

Thank you for the notice. We changed the respective title to "HBV model setup and parameter uncertainty" to better describe the section content.

You need to better emphasize the challenges when separating liquid from solid precipitation within the HBV modelling framework. Maybe you can discuss the implications on your results a little more detailed.

The uncertainty of model parameters is discussed in Section 4.1. We think it is an important topic since many of the model parameters might have an important effect on the result interpretation. Nevertheless, a more detailed discussion of implications resulting from HBV parameterization was suggested also by Referee 1. Therefore, we added more discussion on this topic to Section 4.1 (L 368-385), specifically we extended the discussion related to model parameters T_{T}, S_{FCF} and the calculation of AET. Besides, we newly added a bit of discussion related to the snow routine structure and its possible effect on the ability of the model to simulate snow storages, as newly tested by Girons Lopez et al. (2020) (currently discussed in HESSD).

The contribution from groundwater calculated with HBV is quite uncertain, you could also be looking at generally higher storage potential at higher elevations. Maybe you could consider discussing these uncertainties.

This comment also touches the issue mentioned by Referee 1. It is true that absolute values of groundwater storages simulated by the model may be uncertain since groundwater data were not used to calibrate the model (see also our response to Referee 1). Nevertheless, we were concentrated on relative differences (year-to-year variations) between groundwater fluxes in individual catchments rather than on absolute values. Some studies also showed that catchment storage calculated using different methods (water balance calculations, recession curve analysis, HBV modelling) are, in general, comparable and correlated, although the quantitative estimates may differ (Staudinger et al. 2017). The above study also showed that dynamic groundwater storage is correlated with elevation, indicating the relation of the groundwater storages and snow storages. The relative fraction of groundwater in streams and its sensitivity to inter-annual variations in snow storages was also shown by Carroll et al. (2019).

Therefore, we included more discussion on the ability of the model to simulate the groundwater storage (Section 4.1, L 351-361; see also the response to the respective comment of Referee 1). We also included a bit more discussion in Section 4.2 (L 396-399 and 420-423) related to the catchment storage.

You mention a lot of interesting differences between the regions / catchments in the discussion, maybe you can add more information at an earlier part of the manuscript and build your story on these different regions.

Thank you for the suggestion. We agree and we tried to put more emphasis on regional consequences of our results because we are aware that our results are limited to the specific region and may not be easily generalized. Please, see our answer to your related general comment above to see all changes we did in this respect.

We also thought about some reorganization of the discussion section to better highlight regional differences between our study catchments, but after consideration of all alternatives (and reflecting other changes we did in the discussion section), we decided to keep the structure of the section as it was in the original manuscript.

Conclusions: I'd appreciate if you could relate the statements with the according figures, that makes it easier for the reader to recap on where to find the evidence for the conclusions

Thank you for the suggestion. We added some relevant links to figures to the Conclusion section.

The second objective (lines 86 & 87) is to show the importance of snowmelt "at different elevations", however elevation differences where not really mentioned and I also did not find any concluding remarks regarding this statement.

As we mentioned in one of the comments above, the dependence of individual characteristics on elevation is rather indirect and may not be easy to interpret although the elevation clearly influences the snowfall fraction and thus snow storages. We agree that mentioning the elevation as the most important catchment attribute might be confusing. We reformulated both objectives and discussion to be clearer. Please, see our answer to your related general comment above.

I am also not convinced that I saw results that support that "future liquid precipitation will not compensate the lower solid precipitation", please re-write or leave out.

By this sentence, we wanted to draw the attention to the fact that the future decrease in snow storages might cause a decrease in annual runoff (even despite no changes in total amount of precipitation), and we think it is important to mention it. However, we reformulated the sentence to "Modelling experiments indicated that the future decrease in snowfall fraction together with changes in seasonal runoff distribution might result in lower annual runoff despite no changes in total precipitation."

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Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia

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Keywords. snow, snowmelt runoff, recharge, baseflow, low flow

Abstract. The streamflow seasonality in mountain catchments is ~~largely~~often influenced by snow. However, a shift from snowfall to rain is expected in the future. Consequently, a decrease in snow storage and earlier snowmelt is predicted, which will cause changes ~~in spring and summer runoff.~~not only in seasonal runoff distribution in snow-dominated catchments, but it may also affect the total annual runoff. The objectives of this study were to quantify 1) how inter-annual variations in snow storages affect spring and summer runoff, including summer low flows and 2) the importance of snowmelt in generating runoff compared to rainfall. The snow storage, groundwater recharge and streamflow were simulated for 59 mountain catchments in Czechia in the period 1980–2014 using a bucket-type catchment model. The model ~~performance~~output was evaluated against observed daily runoff and snow water equivalent. Hypothetical ~~simulations~~scenarios were performed, which allowed~~ us~~ to analyse the effect of inter-annual variations in snow storage on seasonal runoff separately from other components of the water balance.

The results showed that 17~~-~~–42% (26% on average) of the total runoff in the study catchments originates as snowmelt, despite the fact that only 12~~-~~–37% (20% on average) of the precipitation falls as snow. This means that snow is more effective in generating catchment runoff compared to liquid precipitation. This was ~~documented~~demonstrated by modelling experiments which showed that total annual runoff and groundwater recharge ~~decreases~~decrease in the case of a precipitation shift from snow to rain. In general, snow-poor years ~~are~~were clearly characterized by a lower snowmelt runoff contribution compared to snow-rich years in the analysed period. Additionally, snowmelt started earlier in these snow-poor years and caused lower groundwater recharge. This also affected summer baseflow. For most of the catchments, the lowest summer baseflow was reached in years with both relatively low summer precipitation and snow storage. This showed that summer low flows (directly related to baseflow) in our study catchments are not only a function of low precipitation and high evapotranspiration, but they are significantly affected by the previous winter snowpack. This effect might intensify ~~the summer low flows~~drought periods in the future when generally less snow is expected.

1 Introduction

Mountain catchments are often influenced by snow, which ~~largely~~significantly affects seasonality in runoff. However, snow water equivalent (SWE) has been decreasing in many mountains regions over the last decades and spring snowmelt ~~occurs~~tends to occur earlier in the year (Beniston, 2012; Fyfe et al., 2017; Harpold et al., 2012; Klein et al., 2016; Marty et al., 2017b). This suggests that snow and snowmelt dynamics respond to ~~increase in~~increasing air temperature ~~and precipitation~~ due to climate ~~changes~~change (Barnett et al., 2005; Bavay et al., 2013; Jenicek et al., 2018; Marty et al., 2017a). The higher air temperature causes a shift from snowfall to rain ~~during winter~~ resulting in lower snowfall fraction, a ~~rate~~proportion of snowfall water equivalent (hereafter referred to as snowfall) to annual precipitation. Consequently, the amount of snow and peak SWE ~~is affected~~are reduced as well (Berghuijs et al., 2014; Jenicek et al., 2016). As a response to increasing temperature, the snowmelt starts earlier in the year, which can result in slower snowmelt rates due to lower available energy, such as solar radiation (Klein et al., 2016; Musselman et al., 2017). ~~On the contrary, water demand of vegetation is lower earlier in the year. Changes in~~Reduced snow ~~accumulations,~~accumulation, and earlier and slower snowmelt ~~timing and snowmelt rates significantly affect~~ cause earlier and lower groundwater recharge ~~which is lower and occurs earlier~~ (Beaulieu et al., 2012; Foster et al., 2016). For the groundwater recharge, the topography is important as the water is transported from steep terrain ~~near~~surrounding mountain ridges to lower ~~elevation~~elevations (Carroll et al., 2019). Therefore, higher elevations are important for catchment storage (Floriancic et al., 2018; Hood and Hayashi, 2015; Staudinger et al., 2017) ~~and important to stabilize~~as well as for stabilizing the streamflow at lower elevations especially during drought periods (Carroll et al., 2019; Cochand et al., 2019). Higher snowpack ~~generates higher~~disproportionally feeds groundwater ~~flow driven by snowmelt rates and thus contributes~~leading to more ~~to~~ streamflow (Barnhart et al., 2016).

The decreasing snow storages and groundwater recharge in mountain regions further influence summer low flows (Dierauer et al., 2018; Ledvinka, 2015; Li et al., 2018; Van Loon et al., 2015; Potopová et al., 2016). Higher snowpack and later snowmelt contribute to summer baseflow and increase the period for which snowmelt contributes to streamflow (Hammond et al., 2018; Langhammer et al., 2015). For catchments at higher elevations, this period may cover the whole summer (Godsey et al., 2014; Jörg-Hess et al., 2014). Earlier snowmelt and melt-out in the future will further shorten this period (Etter et al., 2017; Jenicek et al., 2018). For summer low flows in Europe, the liquid precipitation and evapotranspiration is usually more important than previous winter snow storages (Floriancic et al., 2019), but low snowpack causes a decrease in summer low flows in the case of simultaneously low summer precipitation (Jenicek et al., 2016).

Several earlier studies ~~were~~ focused on identification of physical mechanisms ~~of~~that would help explain how earlier or later snowmelt influences the runoff generation (summarized in Barnhart et al., 2016). One mechanism ~~is~~describes that due to higher air temperature during earlier snowmelt, a greater proportion of snowmelt evaporates (Barnhart et al., 2016; Bosson et al., 2012). In contrast, earlier snowmelt occurs in periods when vegetation is less active, thus ~~uses~~using less water. Therefore, more water flows into the stream. Another effect is that slower snowmelt (associated with earlier snowmelt; Trujillo and Molotch, 2014) leads to lower streamflow generation due to the fact that during later and faster snowmelt, soil moisture might be more often above its capacity leading to higher streamflow. Additionally, higher snowmelt rates lead to higher baseflow (Barnhart et al., 2016). Therefore, it is important to analyse inter-annual variability of snow, climate and streamflow characteristics in areas where snow is an important source for runoff generation.

The role of snow in seasonal catchment runoff, summer low flows and water supply is frequently quantified using several snow-related metrics, such as peak SWE or snowfall fraction (Curry and Zwiers, 2018; Hammond et al., 2018). When a modelling approach is applied, the ratio of snowmelt runoff to total runoff is often used (Jenicek et al., 2018; Li et al., 2017; Stahl et al., 2016). Such approaches enable to quantify the importance of snow in the generation of spring and summer runoff and in the "memory effect" of a specific catchment, i.e., how long snow affects runoff after snowmelt (Godsey et al., 2014; Jenicek et al., 2016). Several studies also showed that snow is more effective in generating the runoff compared to liquid precipitation. For example, in the western United States 53% of the total runoff originates from snowmelt, despite the fact that only 37% of the precipitation falls as snow (Li et al., 2017). The mentioned discrepancy between snowfall amount and snowmelt runoff might have substantial impacts on seasonal distribution of the runoff and water supply in a warming climate, when more rainfall is expected compared to snowfall (Harpold et al., 2017; Safeeq et al., 2016).

Snowfall fraction might be an interesting indicator to what degree snow affects summer low flows. For example, Meriö et al. (2019) found a threshold of snowfall fraction of 0.35 in their study catchments in Finland. In catchments with snowfall fraction above the threshold, the summer low flows were sensitive to inter-annual variations in snow storages. Below the threshold, summer precipitation and air temperature together with catchment characteristics were more important. Although specific thresholds might differ across world regions, the role of snow storages on summer low flows was shown in several studies from Europe and North America (Godsey et al., 2014; Jenicek et al., 2016).

The above studies show that changes in snow storages and their impact on runoff and groundwater recharge are in the centre of the current research. However, there is still a need to investigate mutual interactions between individual characteristics, such as snow storages in snow-poor and snow-rich years and their interaction with groundwater recharge, snowmelt runoff, spring and summer rainfall, summer baseflow and low flows. This is specifically important for assessment of how the changes in snow storages affect seasonal runoff distribution and whether or not they may also affect annual water balance. The need to explain this variability and change of temporal and spatial processes also arose from the hydrology community initiative to identify major unsolved scientific problems in hydrology (Blöschl et al., 2019).

Therefore, the objectives of this study were to quantify 1) how inter-annual variations in snow storages affect spring and summer runoff, including summer low flows and 2) the importance of the snowmelt in generating the runoff compared to rainfall at different elevations~~. The focus on elevation is important since snow storage and its potential change is highly dependent on elevation.~~ with different snowfall fractions. We quantified the influence of inter-annual variability in snow storages on summer runoff and low flows in 59 catchments in Czechia with significant snowmelt contribution to runoff. Focusing on non-alpine region of Central Europe is important, as most of the studies addressing this topic were conducted ~~in~~for alpine ~~region at~~regions characterized by higher elevations and ~~with~~ partly different climate conditions. Therefore, the identification of other snow-dominated regions which might become more vulnerable to drought occurrence in the future is critical. For snowmelt contribution, we used an "effect tracking" algorithm which is now accepted and used by the modelling community aiming to track the effect of individual water sources in the system to assess either the inter-annual variability of runoff components or their potential changes in the future (Weiler et al., 2018).

2 Data and methods

2.1 Study area and input data

~~The~~We selected 59 mountain catchments with minor influence of human activity together with significant snow influence on runoff ~~were selected~~ (Fig. 1, Table 1). An important criterion for the selection was the availability of long-term time series of hydrological and meteorological observations ~~(>~~(~35 years). With our selection, we covered most of the mountain regions of ~~the~~ Czechia, namely the Bohemian Forest (BF, 12 catchments), Ore Mts. (OM, 2 catchments), Western Sudetes (WS, 16 catchments), Central Sudetes (CS, 5 catchments), Eastern Sudetes (ES, 13 catchments) and Western Carpathians (WC, 11 catchments). Although the mean catchment elevation ranges only from 491 to 1297 m a.s.l, all catchments have the seasonal snowpack every year. The mean SWE_{max} for individual catchments ranges from 35 mm for the lowest catchments to 664 mm for the highest catchments (Table 1).

The daily runoff data were available for all closure profiles of the catchments from the Czech Hydrometeorological Institute (CHMI). Similarly, daily precipitation, daily mean air temperature and weekly SWE data from selected climatological stations located within or nearby individual catchments were obtained from the CHMI. Stational data were further used in a hydrological model. All data were available for the period from 1980 to 2014, except three catchments, from which data started in 1981 or 1982.

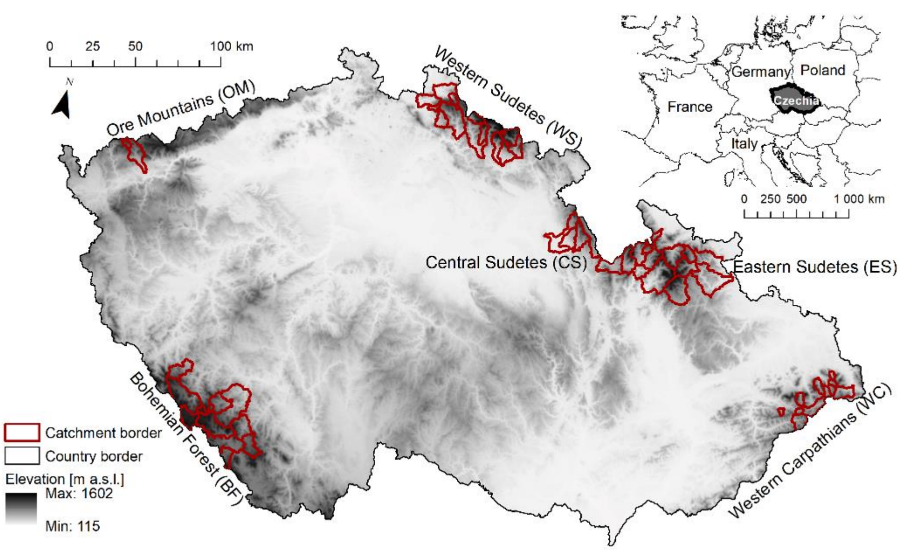

Figure 1: Location of the study catchments in Czechia.

Table 1: Selected characteristics of the study catchments. Catchments IDs are given in the following way: 100 – Bohemian Forest (BF), 200 – Ore Mts. (OM), 300 – Western Sudetes (WS), 400 – Central Sudetes (CS), 500 – Eastern Sudetes (ES), 600 – Western Carpathians (WC). Snowfall fraction, SWE_{max} and snowmelt contribution to runoff represent catchments means (1980–2014) resulting from model simulations.

ID	Name	Station	Area [km²]	Mean elevation [m a.s.l]	Elevation range [m a.s.l]	Mean slope [°]	Snowfall fraction [-]	SWE_{max} [mm]	Snowmelt contribution to runoff [%]
101	Vydra	Modrava	89.8	1140	983–1345	3.7	0.24	187	29
102	Otava	Rejstejn	333.6	1017	598–1345	5.1	0.19	113	22
103	Hamersky	Antygl	20.4	1098	978–1213	3.3	0.21	130	23
104	Ostruzna	Kolinec	92.0	755	541–1165	4.6	0.13	43	17
105	Spulka	Bohumilice	104.6	804	558–1131	4.9	0.13	35	17
106	Volynka	Nemetice	383.4	722	430–1302	4.7	0.13	38	17
107	T. Vltava	Lenora	176.0	1010	765–1314	5.2	0.17	83	22
108	Blanice	Blanicky M.	85.5	892	757–1197	3.5	0.16	45	21
109	Blanice	Podedvor. M.	202.8	844	558–1274	4.6	0.14	37	19
110	Stassky	Novy Dvur	9.9	962	792–1131	6.4	0.17	65	23
111	T. Vltava	Chlum	347.3	939	733–1314	4.9	0.15	66	19
112	S. Vltava	Cerny Kriz	102.4	921	738–1353	4.3	0.15	69	20
201	Rolava	Chaloupky	18.7	902	826–956	2.2	0.26	229	31
202	Rolava	Stara Role	125.3	761	398–994	4.3	0.19	112	24
301	Jerice	Chrastava	76.0	493	295–862	4.7	0.12	50	17
302	C. Nisa	Straz	18.3	672	368–850	4.6	0.19	121	24
303	L. Nisa	Prosec	53.8	611	419–835	4.4	0.17	94	20
304	Smeda	Bily p.	26.5	817	412–1090	8.3	0.29	236	35
305	Smeda	Frydlant	132.7	588	297–1113	5.9	0.18	112	24
306	Jizera	D. Sytová	321.8	771	399–1404	6.4	0.29	241	36
307	Mumlava	Janov	51.3	970	625–1404	7.8	0.33	383	41
308	Jizerka	D. Stepanice	44.2	842	490–1379	8.6	0.25	203	32
310	M. Labe	Prosecne	72.8	731	376–1378	6.3	0.21	131	27
311	Cista	Hostinne	77.4	594	358–1322	5.1	0.16	84	21
312	Modry	Modry dul	2.6	1297	1076–1489	13.0	0.38	664	41
313	Upa	H. Marsov	82.0	1030	581–1495	9.7	0.33	334	41
314	Upa	H. S. Mesto	144.8	902	452–1495	8.6	0.29	245	35
315	C. Nisa	Uhlirska	1.8	816	786–850	2.2	0.28	257	34
316	C. Desna	Jezdecka	4.8	899	792–1007	5.6	0.33	396	38
317	Kamenice	Bohunovsko	178.8	699	345–1069	5.8	0.23	171	28
401	Bela	Castolovice	214.1	491	269–1104	3.3	0.12	59	20
402	Knezna	Rychnov/Kn.	75.4	502	305–861	3.2	0.12	54	18
403	Zdobnice	Slatina/Zd.	84.1	721	395–1092	5.2	0.22	171	30

404	D. Orlice	Klasterec/Orl.	153.6	728	505–1078	4.8	0.19	151	25
405	T. Orlice	Sobkovice	98.5	622	459–965	4.6	0.18	91	25
501	Branna	Jindrichov	90.3	794	474–1378	6.8	0.16	117	21
502	Desna	Sumperk	246.9	736	320–1454	8.2	0.17	89	23
503	Moravice	Velka Stahle	168.6	800	549–1415	5.4	0.23	108	32
504	Opava	Krnov	369.2	668	315–1437	6.0	0.12	53	18
505	Opavice	Krnov	173.3	547	318–912	5.1	0.17	50	25
506	Morava	Vlaske	96.5	790	448–1374	7.9	0.22	160	29
507	Krupa	Habartice	109.3	756	480–1267	6.6	0.26	188	34
508	Telcsky	Stare mesto	21.9	802	548–1102	6.4	0.16	132	20
509	Morava	Raskov	350.0	745	380–1378	6.9	0.25	165	33
510	Bela	Jesenik	118.0	799	443–1390	8.4	0.22	124	27
511	Stribrny	Zulova	21.4	712	390–1108	7.7	0.14	91	17
512	C. Opava	Mnichov	51.0	814	579–1186	6.6	0.16	88	18
513	Opava	Karlovice	150.9	854	503–1437	8.0	0.18	99	21
601	V. Becva	V. Karlovice	68.3	749	524–1042	6.8	0.17	107	22
602	R. Becva	H. Becva	14.1	745	568–966	7.0	0.21	130	27
603	Celadenka	Celadna	31.0	803	536–1187	9.9	0.21	124	27
604	Ostravice	S. Hamry	73.3	707	542–922	5.9	0.21	128	27
605	Moravka	Uspolka	22.2	763	560–1104	8.1	0.23	142	28
606	Skalka	Uspolka	18.9	785	571–1029	8.1	0.24	148	29
607	Lomna	Jablunkov	69.9	667	390–1011	7.5	0.19	96	23
608	Mohelnice	Raskovice	35.4	765	473–1209	10.3	0.22	131	27
609	Slavic	Slavic	15.1	827	575–1016	10.4	0.23	148	28
610	Ropicanka	Reka	12.2	696	454–1008	10.9	0.21	118	26
611	Lesti	Solanec	10.4	700	513–874	6.7	0.17	104	22

2.2 HBV model

To assess the impact of inter-annual variability of snow on streamflow, we need to simulate individual components of the rainfall-runoff process at a catchment level. For this, we used a bucket-type HBV model (Lindström et al., 1997) in its software implementation~~, called~~ HBV-light (Seibert and Vis, 2012). Details ~~for~~on the model structure and routines are described in several studies (Jenicek et al., 2018; Seibert and Vis, 2012).

The study catchments were sub-divided into elevation zones by 100 m reflecting the changes of precipitation and temperature with elevation. The time series of daily precipitation, daily mean air temperature and monthly potential evapotranspiration (P_{ET}) represent the main model inputs. The temperature-based method described by Oudin et al. (2005) was used for P_{ET} calculation.

The HBV model was calibrated for each catchment against observed runoff and SWE using a genetic calibration algorithm (Seibert, 2000). The integrated multi-variable model calibration approach was applied using a combination of three goodness-of-fit criteria (Table ~~1~~2); 1) model efficiency for runoff using logarithmic values (R_{runoff}) (Nash and Sutcliffe, 1970), 2) model efficiency for SWE (R_{SWE}) and 3) volume error (R_{vol}). The resulting objective function (R_{weighted}) was calculated from these three criteria as a weighted average with a, b and c representing the weights for each criterion. Different weights were tested based on our experience with the model to ~~achieve the best~~produce as accurate as possible ~~performance of the model~~simulations considering both high and low flows, water balance and snow storages.

Table 2: Objective functions used for model calibration and validation.

Objective function	Equation	Weights
Model efficiency for runoff	$R_{\mathrm{runoff}} = 1 - \frac{\sum(\ln Q_{\mathrm{obs}} - \ln Q_{\mathrm{sim}})^2}{\sum(\ln Q_{\mathrm{obs}} - \overline{\ln Q_{\mathrm{obs}}})^2}$	60%
Model efficiency for SWE	$R_{\mathrm{SWE}} = 1 - \frac{\sum(SWE_{\mathrm{obs}} - SWE_{\mathrm{sim}})^2}{\sum(SWE_{\mathrm{obs}} - \overline{SWE_{\mathrm{obs}}})^2}$	20%
Volume error	$R_{\mathrm{vol}} = 1 - \frac{\lvert\sum(Q_{\mathrm{obs}} - Q_{\mathrm{sim}})\rvert}{\sum(Q_{\mathrm{obs}})}$	20%
Weighted efficiency	$R_{\mathrm{weighted}} = a\cdot R_{\mathrm{runoff}} + b\cdot R_{\mathrm{SWE}} + c\cdot R_{\mathrm{vol}}$	n.a.

The observed time series were divided in two sub-series; first (1980-1997) was used for model calibration, second (1998-2014) for model validation. The two periods covered both cold and warm years and wet and dry years. Although mean annual air temperature increased by 0.7°C for the validation period, annual precipitation and peak SWE did not ~~change~~differ significantly between both periods~~.~~ (mean SWE_{max} was 141 mm for the calibration period and 140 mm for the validation period; annual precipitation was 1104 mm for the calibration period and 1143 mm for the validation period).

The parameter uncertainty was addressed by performing 100 calibration runs resulting in 100 parameter sets. These 100 sets were further used to create 100 simulations. A median simulation was used for further analyses. This median simulation was derived in a way, that individual daily values for specific simulated variables (runoff, SWE, groundwater recharge etc.) were calculated as a median from all 100 respective values resulting from simulations. ~~The similar procedures~~This procedure for the model set-up and calibration was also used ~~earlier~~ in ~~(Jenicek et al., 2018)~~Jenicek et al. (2018), although ~~in~~for a different region.

2.3 Modelling experiments

To study the effect of inter-annual variations in snow storages on seasonal runoff characteristics (such as baseflow, deficit volumes and recharge) separately from other meteorological controls (mainly liquid precipitation and actual evapotranspiration, A_{ET}), the hypothetical ~~simulations~~scenarios were ~~performed~~modelled. These simulations consist in changing the threshold temperature T_{T} (a parameter included in the HBV snow routine) which is used to differentiates between snow and rain. By changing the T_T, we can control the amount of accumulated snow and snowmelt timing, while other variables remain unaffected (such as total amount of precipitation). Therefore, the T_T was progressively changed from -5°C to +5°C. Changes in this parameter influenced the simulated snowfall and thus SWE, snowmelt onset, melt rates and melt-out. The experiment was applied to the whole study period and thus capturing a variety of meteorological conditions. In this experiment, the snowfall correction factor (S_{FCF}) correcting solid precipitation for the undercatch, was set to "1" (meaning no correction applied to original input precipitation data). Similarly, P_{ET} was not adjusted according to the inter-annual variations in air temperature (meaning only input daily P_{ET} was used, calculated from long term data as described earlier). This enabled a separation of the effect of changing T_T on snow characteristics and seasonal runoff from other potential effects. With this procedure, we were able to attribute simulated runoff changes to changes in winter conditions.

2.4 Snow and streamflow signatures

We calculated several snow, groundwater and streamflow characteristics to analyse the impact of inter-annual variations in snow accumulations on seasonal runoff. These characteristics were calculated from median simulations as described in ~~the~~ Section 2.2.

Snow conditions for individual years of the study period were represented by February to May maximum SWE (SWE_{max}) which represents the late winter snow maximum. The snowfall fraction (S_f) describes the phase of precipitation. The snowfall fraction was calculated as the fraction of annual snowfall to annual precipitation using a single threshold temperature T_T. The ~~value~~values of T_T for individual catchments resulted from the model calibration ~~of the specific catchment~~and ranged from -1.58°C to 1.13°C.

The snow component of the streamflow (Q_s) was simulated by the HBV model. The method to track both rain and snow components, so called "effect tracking", is based on complete mixing of the two components in a "virtual mixing tank" (Stahl et al., 2016; Weiler et al., 2018). There are two assumptions for calculation; 1) the liquid water occurring in the snowpack is either considered as snow (in the case of melt of the snowpack) or rain (in the case of rain on snow), 2) when refreezing of the liquid water in the snowpack is simulated, the source is considered as snow. The two assumptions mean that the source of the input water (precipitation) can be changed only from rain to snow by refreezing. However, this process is rather negligible in absolute terms. Both daily and seasonal snow runoff (Q_s) and the fraction of snow runoff to annual runoff (Q_{sf}) ~~was~~were used in further ~~analysis~~analyses.

The groundwater recharge (G_w) was simulated by the HBV model. It represents the outflow from the soil box into groundwater boxes defined by the model (Seibert and Vis, 2012). From simulated time series, the fraction of winter (Dec-Feb, $G_{w\text{-}DJF}$) and spring (March-May, $G_{w\text{-}MAM}$) recharges to total annual recharge were calculated.

While the winter and spring recharge is a useful indicator to show how snow contributes to groundwater storage, the summer baseflow is related to the state of groundwater storage and thus represents both summer precipitation inputs and previous (spring) precipitation and snowmelt groundwater recharge. The summer (June to August, JJA) baseflow (Q_b) was calculated by the HBV model as an outflow from the lower groundwater box (S_{LZ}) which is a part of the model's response routine. The inflow into the S_{LZ} is controlled by percolation (parameter P_{ERC}, mm d^{-1}) and outflow is controlled by a recession coefficient K_2 [d^{-1}] (Seibert and Vis, 2012).

The deficit volume (D_v) represents a water volume lacking in rivers below the defined threshold (Van Loon, 2015). Therefore, it is used as a measure to describe hydrological drought conditions. We used 90th percentile of the flow duration curve. We also tested the 75th percentile without any major impact on the results. We used a variable level threshold method which uses different thresholds calculated separately for individual months in summer (June to August).

To show the inter-annual and seasonal differences in snow runoff in study catchments, most of the signatures were calculated for relatively snow-rich years and relatively snow-poor years. The snow-rich years were defined as years with annual SWE_{max} above the third quartile of the study period (1980-2014), while the snow-poor years represent years with annual SWE_{max} below the first quartile of the study period.

3 Results

3.1 Model calibration and validation

The results arising from model testing showed the overall good performance of the model both for the calibration and validation periods (Fig. 2). The model accurately simulated ~~correctly~~ both runoff (R_{runoff}, R_{vol}) and SWE (R_{SWE}). The SWE was reproduced better at higher elevation catchments which contributed to mostly high agreement of observed and simulated runoff in terms of water balance and runoff seasonality. The calibration period shows slightly higher values of individual objective functions compared to those from the validation period. The results for the validation period represent more realistic model performance since calibration values represent rather the theoretically best possible model performance at the specific catchment.

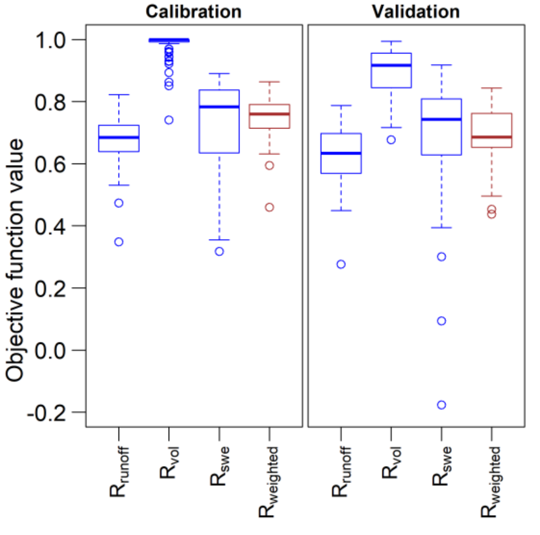

Figure 2: Results of model calibration and validation for study catchments. The objective function value for each catchment represents a median from 100 parameter sets. Boxes represent 25th and 75th percentile (with median as a thick line), whiskers represent 1.5 multiplier of interquartile range.

3.2 Relative importance of snow ~~on~~to runoff during snow-poor and snow-rich years

The snowmelt is more effective in generating the runoff compared to liquid precipitation (Fig. 3). On average, 26% of the ~~total~~annual runoff originated as snowmelt in our study catchments (17~~-~~–42% for individual catchments for the study period), despite the fact that only 20% (12~~-~~–37%) of the annual precipitation occurred as snow (Fig. 3a). Additionally, catchment runoff coefficients (the ratio between catchment precipitation and runoff) ~~are~~were higher for annual snowfall to snowmelt runoff than for annual rainfall to rainfall runoff (results not shown). The higher runoff fraction for snow-generated runoff is caused mainly by lower actual evapotranspiration during winter. Both S_f and Q_{sf} are lower for snow-poor years (brown points) compared to snow-rich years (blue points). It also seems that the difference between Q_{sf} and S_f was higher for snow-rich years (up to 12% for some catchments) and increased with elevation for catchments where the snow is relatively more important in generating the runoff (Fig. 3b, p value < 0.001). These results might have important implications for annual runoff volume in the future when the decrease in snowfall fraction is expected.

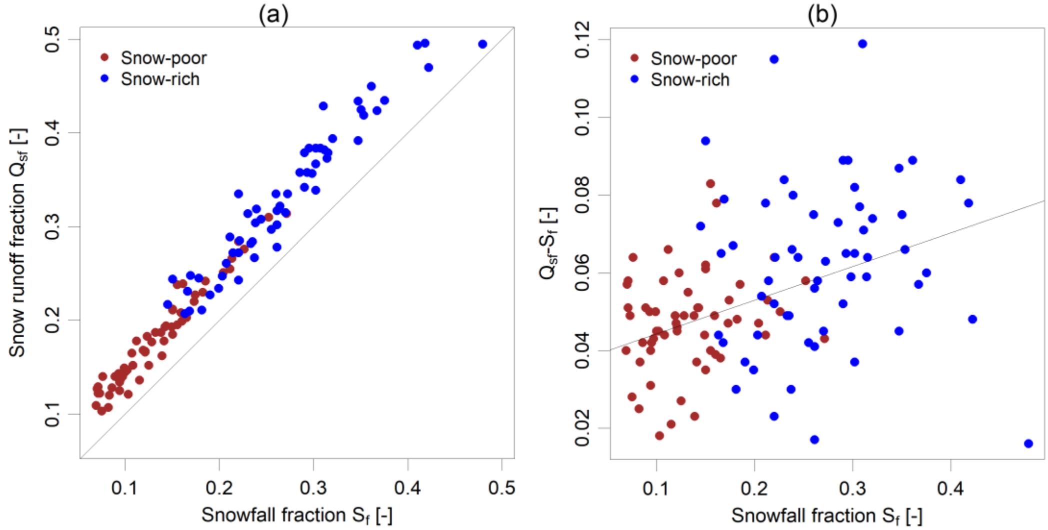

Figure 3: (a) A relation between snowfall fraction (S_f) and snow runoff fraction (Q_{sf}) for all study catchments. (b) A dependence of Q_{sf} and S_f difference on snowfall fraction. ~~Brown~~Individual points represent ~~individual catchments during~~mean snowfall fractions and snow runoff fractions for snow-poor ~~winters;~~ years (brown points) and snow-rich years (blue points ~~represent~~) for individual catchments ~~during snow-rich winters~~.

To show the seasonal distribution of snow runoff in study catchments, we calculated the relative contribution of snow runoff on total runoff (Q_{sf}) as an average for each day of the year. Then we compared this relative contribution of snow runoff for relatively snow-poor years and snow-rich years (Fig. 4a). The figure shows a significantly lower snowmelt contribution for snow-poor years (up to 40%) in all catchments. The largest decrease in Q_{sf} occurred at the end of April/beginning of May in the highest elevation catchments. This largest decrease in Q_{sf} is somewhat shifted towards March in lower elevation catchments indicating that the snow runoff in lower elevation catchments occurs earlier in the year due to higher air temperatures and thus earlier snowmelt onset.

In contrast, there was an increase in relative snow contribution to runoff during snow-poor years in winter, which indicates that snow poor years were usually warmer compared to snow-rich years and thus the runoff increased due to more snowmelt periods during winter (Fig. 4a). Additionally, the decrease in relative snow runoff contribution also occurred during summer (June-August) which indicates that snow melted earlier in snow-poor years and less contributed to spring groundwater recharge and thus summer runoff.

While Fig. 4a shows the snow contribution to total runoff (Q_{sf}), Fig. 4b shows monthly differences in simulated total runoff for snow-poor and snow-rich years for four selected catchments (Vydra, C. Nisa, Desna and Ostravice, see Table 1) representing different geographical regions (four different regions), geology (granite rock, metamorphic rock or flysch) and elevations. As expected, March to May (sometimes even June) runoff was much lower for snow-poor years compared to snow-rich years due to lower snow storages and thus snowmelt runoff. In contrast, winter runoff increased in snow-poor winters due to more rain than snowfall (lower S_f) and thus winter runoff occurred without delay. Summer runoff differed little between snow-rich and snow-poor years. Interestingly, total annual runoff in snow-poor years was often much lower compared to snow-rich years. This may be partly explained by higher effectiveness of snowfall to generate the runoff (Fig. 3) or by the fact that less snow in specific years was connected not only to warmer air temperatures, but also to the lack of precipitation (results not shown). Therefore, this lack of winter precipitation caused the decrease in total annual runoff depth in our study catchments during snow-poor years.

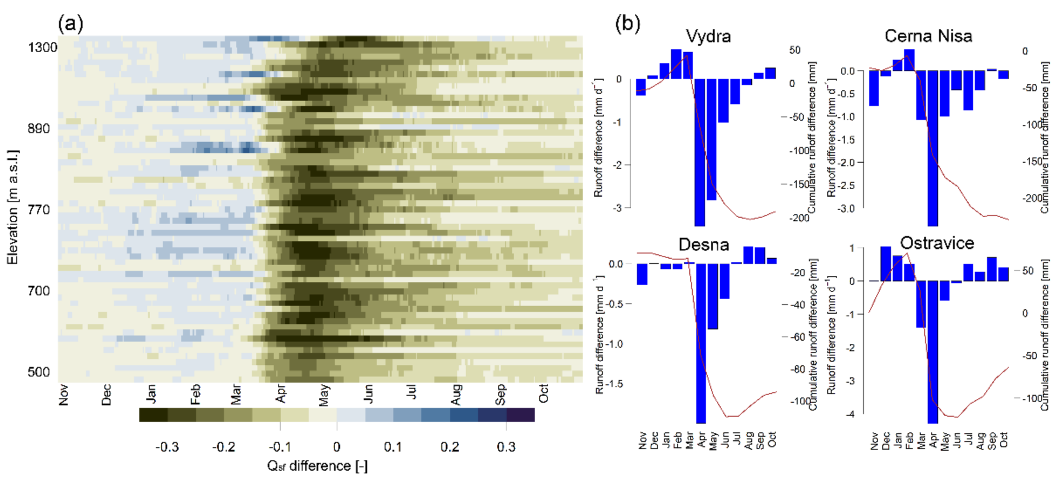

Figure 4: (a) Difference between mean daily Q_{sf} [-] for snow-poor and snow-rich years. Rows represent individual catchments ~~(~~sorted from top to bottom according to mean catchment elevation from highest to lowest (y-axis not-to-scale), columns represent day of year. (b) Difference between mean monthly runoff (blue bars) and cumulative monthly differences in runoff (red line) for snow-poor and snow-rich years; (b1) Vydra (Bohemian Forest), (b2) Cerna Nisa (Western Sudetes), (b3) Desna (Eastern Sudetes), (b4) Ostravice (Western Carpathians).

Lower snow storages in snow-poor years compared to snow-rich years led to lower snowmelt runoff contribution (Fig. 5a) and thus lower seasonal groundwater recharge. This seasonal recharge was expressed as a fraction of December to May recharge on total annual recharge (Fig. 5b). These recharge fractions are clearly lower for the entire cold season for snow-poor years in 57 out of 59 catchments (97%), with higher differences for catchments with higher S_f. However, recharge fractions were higher for the period from December to February (DJF) and lower from March to May (MAM) for snow-poor years (not shown) indicating that winter liquid precipitation during snow-poor years led to higher recharge during winter and thus partly compensated the lower recharge fraction during spring. The lower seasonal recharge fraction also caused lower annual recharge for snow-poor years compared to snow-rich years despite the fact that annual precipitation was almost the same for both groups (results not shown). Lower annual groundwater recharges probably caused lower annual runoff in snow-poor years compared to snow-rich years (Fig. 5c). This partial result supports the results shown in Fig. 3.

Lower snow storages, snowmelt runoff and spring recharge also caused lower summer baseflow in 42 out of 59 catchments (71%), although only for 26 catchments was the difference higher than 5 mm (a sum for JJA period), affecting partly catchments with higher S_f (Fig. 5d). Additionally, summer baseflow strongly negatively correlates with summer deficit volumes (median Spearman rank correlation for all catchments reached the value of -0.8). It resulted in higher summer deficit volumes in snow-poor years compared to snow-rich years for 47 out of 59 catchments (80%, Fig. 5e). Additionally, the difference in deficit volumes between snow-poor and snow-rich years was negatively correlated (p value < 0.05) with difference in snowmelt runoff between snow-poor and snow-rich years with usually larger absolute difference for catchments with higher S_f (Fig. 5f).

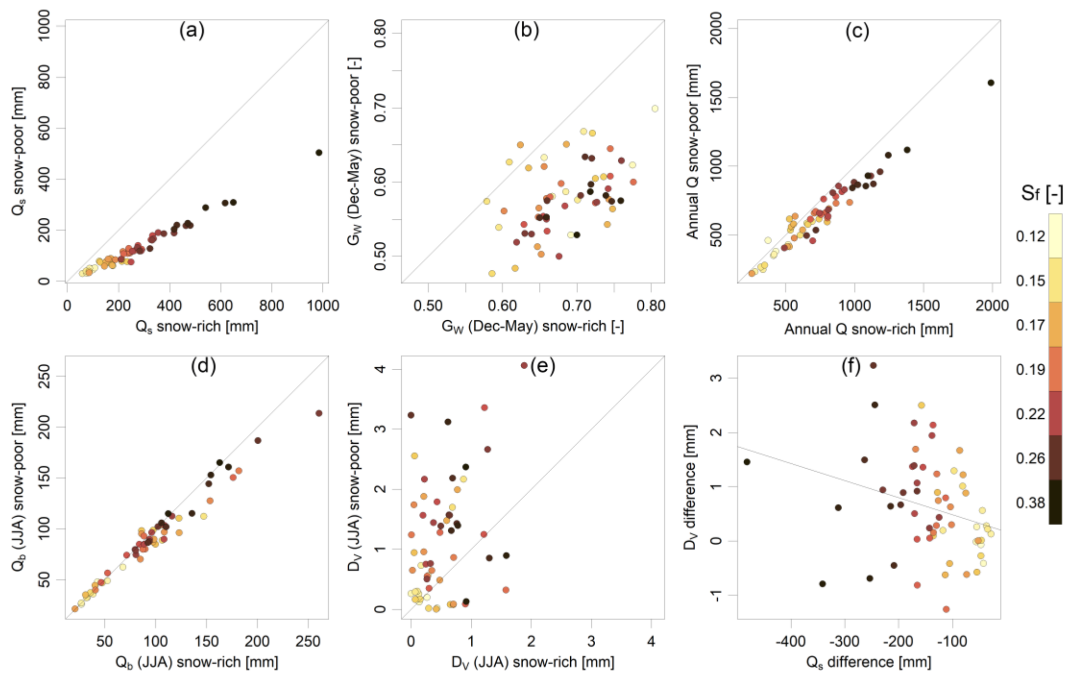

Figure 5: Difference in selected signatures for snow-rich and snow-poor years for study catchments; (a) Annual snowmelt runoff Q_s, (b) Seasonal recharge fractions G_W (Dec–May), (c) Annual runoff Q, (d) Summer baseflow Q_b (JJA), (e) Deficit volumes D_V (JJA),

(f) Relation of deficit volumes D_V (JJA) difference ~~and~~to snow runoff Q_s difference between snow-poor and snow-rich years. Colour scale used for snowfall fraction.

Figure 4 and Fig. 5 showed that less snow led to lower snowmelt contribution to total runoff and to lower winter and spring groundwater recharge. Besides, there was lower baseflow and higher deficit volumes in most catchments in snow-poor years. However, the figures do not provide us with information about how important snow storages are in influencing summer baseflow and deficit volumes compared to summer precipitation. Therefore, we analysed the relation between relative anomalies in summer (JJA) precipitation and relative anomalies in SWE_{max} compared to summer baseflow (Fig. 6). For this analysis, the same four catchments, as previously shown in Fig. 4, were selected to ~~show~~demonstrate that summer baseflow is associated with both summer precipitation and annual SWE_{max} (Fig. 6). The lowest summer baseflow is associated with both the lowest summer precipitation and SWE_{max} (dark brown points are mostly located in the bottom left quadrants in individual panels of Fig. 6). Although, summer precipitation seems to be more important for baseflow amount, Fig. 6 indicates that for some unit precipitation amount, the baseflow was lower for years with low annual SWE_{max}. Nevertheless, the described behaviour differs for individual catchments. For example, the summer precipitation seems to be crucial for summer baseflow in the Ostravice catchment (Fig. 6d), while snow does not play an important role in influencing summer baseflow (the darkest brown points are located roughly equally in both bottom-left and bottom-right quadrants).

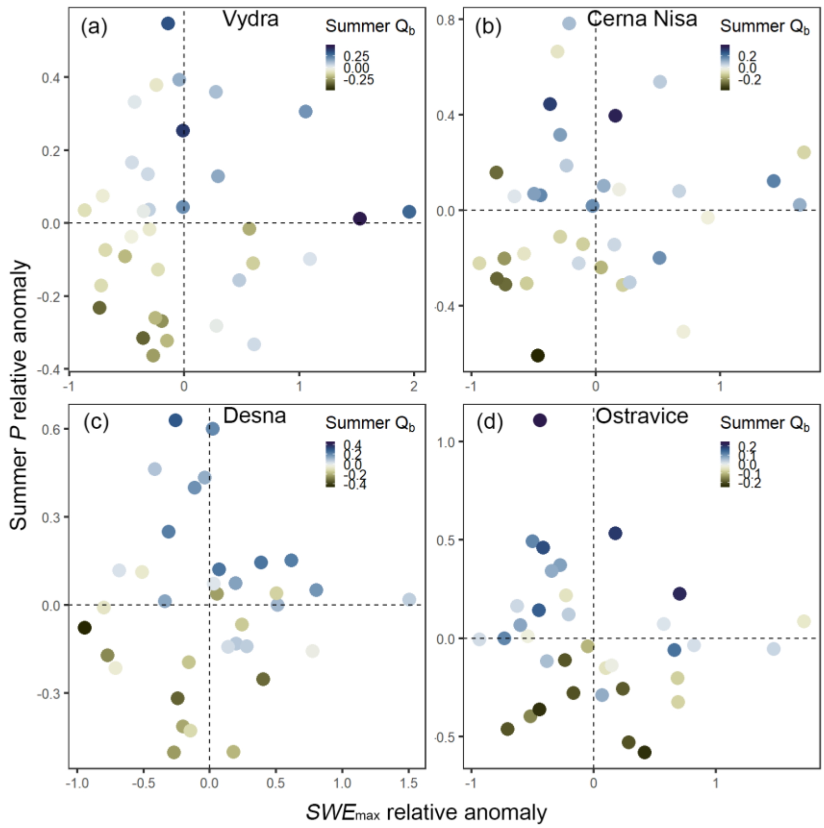

Figure 6: Dependence of summer baseflow (Q_b) relative anomalies on SWE_{max} and summer (JJA) precipitation relative anomalies at four selected catchments. (a) Vydra (Bohemian Forest), (b) Cerna Nisa (Western Sudetes), (c) Desna (Eastern Sudetes), (d) Ostravice (Western Carpathians)

Similar mutual ~~relations of~~relationships between SWE_{max}, summer precipitation and summer baseflow, as shown in Fig. 6, were explored and generalized for all catchments (Fig. ~~7).~~7) to present the relative importance of annual SWE_{max} and summer precipitation to summer baseflow. Figure 7a ~~shows~~depicts the median summer baseflow relative anomalies for years with below-average summer precipitation (*x*-axis) against the median summer baseflow relative anomalies for years with below-average SWE_{max} (*y*-axis). The Figure 7 revealed that 1) below-average summer baseflow occurred for 58 ~~from~~out of 59 catchments (98%) for below-average summer precipitation (points located to the left ~~from~~of the x=0 line) and for 40 out of 59 catchments (68%) for below-average SWE_{max} (points located below the y=0 line) and 2) below-average summer precipitation ~~generates~~generated lower baseflow than below-average SWE_{max} (points located above the one-to-one line). This implies that snow is important in generating baseflow in our study catchments, but summer precipitation is more important. This is specifically valid for catchments in the Eastern Sudetes (ES) and Western Carpathians (WC) where summer precipitation seems to be the dominant driver for summer baseflow generation (the darkest points in Fig. 7a are located above the y=0 line and thus show positive baseflow anomalies for below-average SWE_{max}).

Figure 7b shows that baseflow is lowest for both below-average precipitation and below-average SWE_{max}. However, for 41 out of 59 catchments (69%), the baseflow for years with below-average precipitation increased when there was simultaneously above-average SWE_{max} (points are located above the one-to-one line). ~~Besides, it shows that~~Moreover, 13 out of 59 catchments (22%) ~~generated above-average~~ showed even positive summer baseflow anomalies for above-average SWE_{max} despite ~~below-average~~the negative anomaly of the summer precipitation ~~thanks to above-average SWE_{max}~~ (points located above the y=0 line). For those catchments (mostly smaller catchments with a greater proportion of area at higher elevations), snow storages seem to be more important for summer baseflow than summer precipitation.

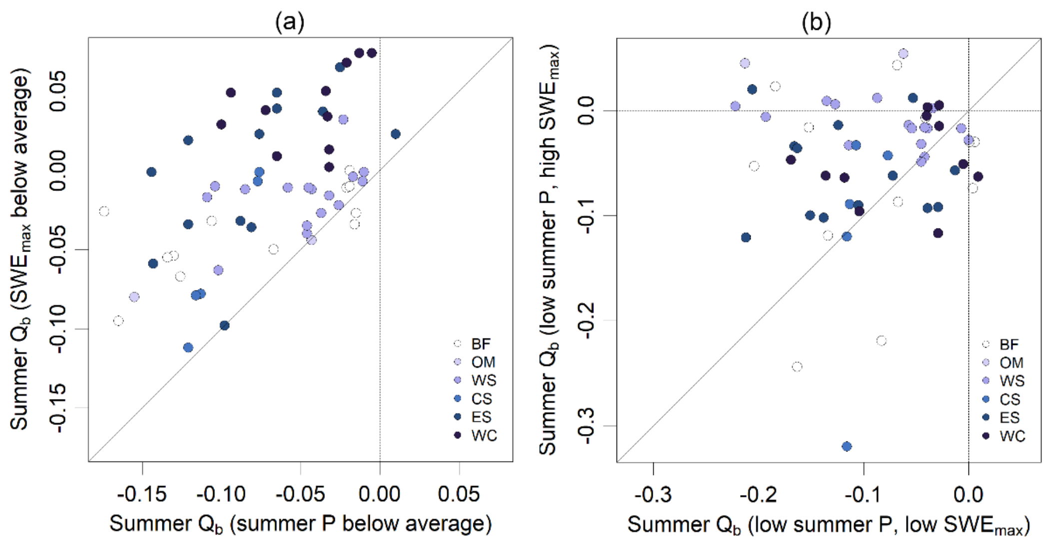

Figure 7: (a) Relation of median summer baseflow for years with below-average summer precipitation and years with below-average SWE_{max}. (b) Median summer baseflow for years with both below-average summer precipitation and below-average SWE_{max} related to median summer baseflow for years with both below-average summer precipitation and above-average SWE_{max}. Points represent individual catchments, colour represents region of the specific catchment (see ~~the~~ Section 2.1 for region abbreviations).

3.3 Modelling changes in runoff for ~~snow~~snowfall-rain transition

The results presented in ~~the~~ Section 3.1 indicated that less snow caused a decrease in spring recharge and thus a decrease in summer baseflow and an increase in summer deficit volumes. However, the above approach did not allow to fully split the effect of snow storages on summer runoff from the effects of other meteorological drivers, mainly summer precipitation and A_{ET}. Therefore, we performed a simple modelling experiment simulating the transition of snowfall to rain while the total annual precipitation and air temperature remained unchanged (see methods).

The model simulated lower snowfall and thus decrease in snow storages and shorter snow-covered season as a response to threshold temperature T_T increase (result not shown). This snow storages decrease caused a decrease in both annual and summer runoff for all 59 catchments (Fig. 8a, Fig. 8b). Simulated snow decrease resulted in lower groundwater recharge in winter and spring for 56 out of 59 catchments (95%, Fig. 8c). Expectedly, the groundwater recharge increased in winter months

(Dec-Feb) thanks to earlier snowmelt and lower S_f (and thus rain infiltrated into the soil immediately). However, the decrease in groundwater recharge in spring (March-May) was much larger than the increase in recharge in winter (not shown), resulting in an overall decrease in Dec-May recharge.

While the decrease in both summer and annual runoff provides the information about overall water availability regardless of the seasonal distribution and extreme situations, the summer deficit volumes provide information about water availability during most critical situations, such as summer low flows. The modelling experiment showed an increasing trend in deficit volumes with decreasing S_f for most of the catchments (Fig. 8d). In contrast to the decrease in annual runoff with decreasing S_f, which was simulated for all study catchments, the increase in summer deficit volumes was simulated only for 34 out of 59 catchments (58%). The remaining catchments do not show clear tendency of deficit volumes or they behave in the opposite direction, which indicates more complex behaviour of such catchments (e.g. due to specific catchment properties, such as geology or slope steepness). However, when looking at June to August deficit volumes separately, the deficit volumes increased for 80% of the catchments in June, for 52% in July, and for 55% in August (results not shown). This evolution suggested the decreasing role of snow in influencing deficit volumes in the analysed months. Similar results as for summer deficit volumes were also achieved for the number of days with deficit volumes, which also mostly increased when the snowfall fraction decreased (results not shown).

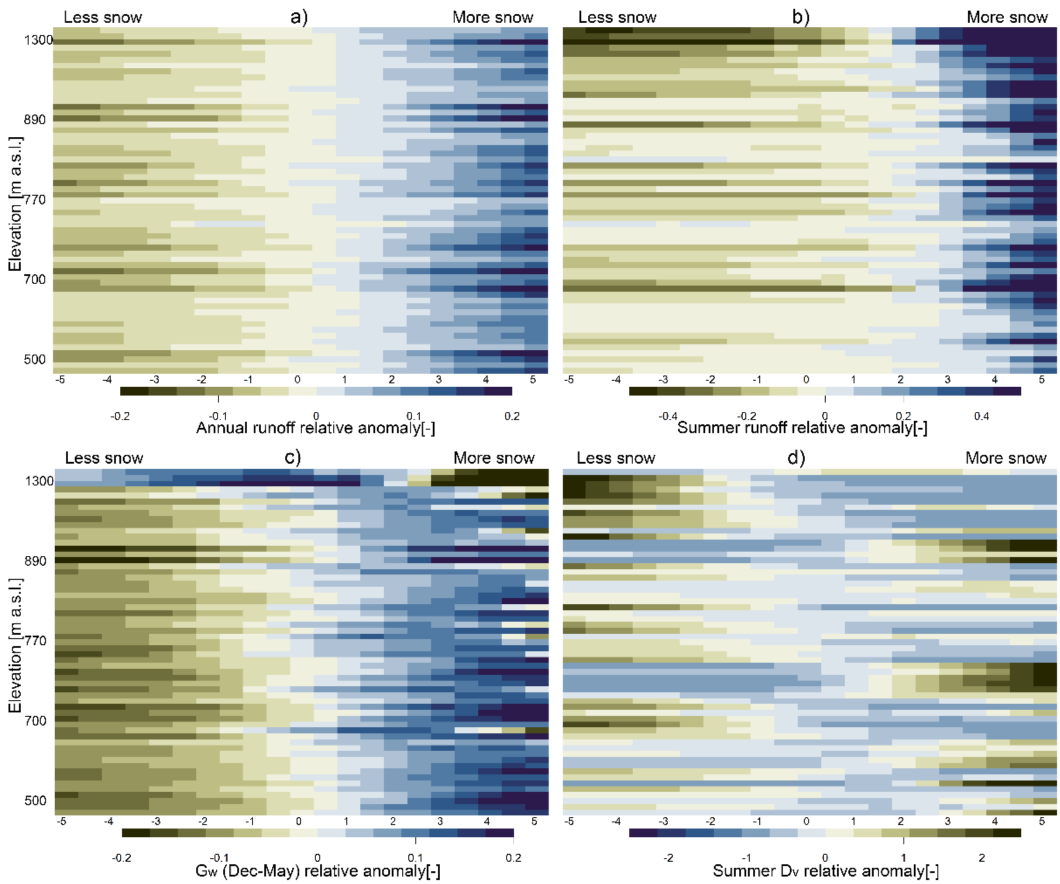

Figure 8: Relative change of selected signatures with increasing T_T for study catchments. (a) annual runoff, (b) summer (JJA) runoff, (c) groundwater recharge (Dec-May) and (d) summer (JJA) deficit volumes. Rows represent individual catchments (sorted from top to bottom according to mean catchment elevation from highest to lowest (y-axis not-to-scale), columns represent T_T used in model simulations. Colours show normalized values relative to their means (different scales used for individual panels).

4 Discussion

4.1 ~~Data errors,~~ HBV model set-up and parameters uncertainty

Since the presented results are based on HBV model runoff simulations, the uncertainty arising from the model parametrization needs to be addressed. This was done by 100 model calibration trials resulting in 100 parameter sets. This way the model generated more robust results. Additionally, a multi-variable approach was used for calibration to correctly simulate both SWE and runoff. This procedure led to better model performance especially in higher elevation catchments with higher snowpack as also shown in other studies (Etter et al., 2017; Jenicek et al., 2018; Seibert, 2000).

The interpretation of our results partly relies on the ability of the model to simulate groundwater storage. Although the model allows to use the groundwater level for calibration, next to discharge and SWE, we did not use the groundwater observations to calibrate the model. The reason was that the density of the measuring network does not allow to find the groundwater stations (either boreholes or springs as a proxy) which would sufficiently represent the whole catchment since the spatial variability in groundwater storages in a catchment is very large due to the variability in geology and soils. In contrast, the streamflow used to calibrate the model represents the integrated output from the whole catchment, and also the observed SWE data usually represents the catchment snow storage well enough (at least at a specific elevation zone). Additionally, we were concentrated on relative differences (year-to-year variations) between groundwater fluxes in individual catchments rather than on absolute values. Some studies also showed that catchment storage calculated using different methods (water balance calculations, recession curve analysis, HBV modelling) are, in general, comparable and correlated, although the quantitative estimates may differ (Staudinger et al., 2017).

There are several issues related to model parametrization ~~and calibration~~. Many of the model parameters might have an important effect on result interpretation. For example, P_{ET} calculated for a specific day did not account for actual air temperature on that day, but it only reflected long-term mean of daily air temperature for the full study period (1980–2014). This affected simulated P_{ET} values which then did not reflect inter-annual variability due to inter-annual variability of air temperature. Nevertheless, by neglecting the potential feedbacks from P_{ET} inter-annual variability, this approach enabled a better separation of snow influence on summer low flows.

Modelling experiments also opened further questions related to model structure and parameterization, specifically how individual model procedures and parameters represent the real natural processes. For example, a snowfall correction factor (S_{FCF}) is used in the model to correct solid precipitation for the undercatch (e.g. due to wind). Nevertheless, it may also compensate some processes not explicitly included in the model, such as snow interception, sublimation and A_{ET} from snow cover. Similarly, threshold temperature T_T used in our modelling experiment to control snowfall fraction is also used to set the snowmelt onset and as a threshold temperature to distinguish whether the S_{FCF} will be applied or not. Therefore, S_{FCF} was set to "1" in the modelling experiment to avoid modification of the solid precipitation amount throughout the experiment and thus entire water balance. ~~The above-mentioned potential model artefacts~~For the future model development, it might by therefore useful to set one T_T for snow/rain separation and another T_T for snowfall correction. Similarly, the calculation of A_{ET} during existing snow cover on the ground might be beneficial.

For studies performed in snow-dominated catchments, it is also important how well (or badly) the model simulates snow storages at different elevations. For example, Girons Lopez et al. (2020) tested several modifications of the HBV model snow routine in Swiss and Czech catchments (a subset of those used in this study) and showed that the snow routine employed in the HBV model provided relatively good results, although some modifications might be worth consideration, such as using seasonally-variable melt factor or exponential snowmelt function. Nevertheless, an increased model complexity does not necessarily mean the better model ability to reproduce SWE and runoff (Girons Lopez et al., 2020). The above-mentioned parameter issues might be important when using HBV or similar bucket-type models for impact studies, such as modelling the impact of climate change on catchment runoff.

4.2 Influence of snow storages on snowmelt runoff and groundwater recharge

The results showed that the fraction of runoff originating as snowmelt is by 2~~–~~–12% higher than the fraction of precipitation occurring as snow (higher values for snow-rich years and for catchments at higher elevation). This indicates that snowmelt is more effective in generating runoff compared to liquid precipitation~~. This interesting effect was also shown by Li et al. (2017) in the western United States using a similar modelling approach and it also supports~~ in the study catchments. The reason for such behaviour is lower A_{ET} during winter and lower water demand by vegetation (the latter is not included in the HBV model structure), both resulting in lower precipitation losses.~~ results achieved by Berghuijs et al. (2014) who showed that higher snowfall fractions generates higher annual runoff in the western United States. The reason for such behaviour is probably due to a lower A_{ET} during winter and lower water demand by vegetation, both resulting in lower precipitation losses.~~ Besides, the A_{ET} is calculated only for a snow-free ground in the HBV model. Another reason might result from the fact that soil moisture is more often at its field capacity, thus the model also simulates higher runoff during snowmelt events (Barnhart et al., 2016; Li et al., 2017). In other words, snowmelt rates control the relative partitioning of snowmelt water between evapotranspiration and streamflow (Barnhart et al., 2016).

Nevertheless, in absolute values, snowfall represented a higher water volume than runoff from snow which comes out from the definition of the "effect tracking" algorithm in HBV (as described in Section 2.4). However, in few catchments it happened that few hydrological years showed higher snowmelt runoff than snowfall in that year since part of this snowmelt contribution came from the previous year (probably thanks to a long catchment storage). The mentioned effect is certainly worth investigating further, but it goes beyond the scope of the current study.

The effect of a higher snowmelt runoff fraction than snowfall fraction was also shown by Li et al. (2017) in the western United States using a similar modelling approach and it is also supported by the results achieved by Berghuijs et al. (2014) who showed that higher snowfall fractions generate higher annual runoff in the western United States. Although our results are limited to the study catchments and may not be easily generalized, the described catchment behaviour might have an important impact on runoff generation in the future, where the shift from snow to rain during winter is predicted due to the increase in air temperature (Jenicek et al., 2018).

The results showed that the contribution of snow to runoff is much lower for snow-poor than snow-rich years~~.~~ in the study catchments. The decrease was obvious also for the period from June to August, indicating that snow also contributed to summer runoff for snow-rich years. The snow contribution to summer runoff, including low flows, was also ~~shown~~documented by several other studies (Godsey et al., 2014; Jenicek et al., 2016; Stahl et al., 2016), although mostly for higher elevation catchments with later snowmelt compared to our study catchments. The summer snow runoff originates from spring snowmelt, which propagated into deeper groundwater layers and contributed to runoff with delay. The snow runoff contribution was calculated using the "effect ~~-~~tracking" algorithm implemented in the HBV model using "virtual mixing tanks" with limited capacities. The method was tested within several studies (Stahl et al., 2016; Weiler et al., 2018). The algorithm is a useful approach to assess changes in discharge components (Weiler et al., 2018).

The average contribution of groundwater to streamflow was from 22% to 84%, with higher values for catchments with generally higher snowfall fractions and thus higher snow storages. However, besides snow amounts, some other regional differences were found. For example, catchments in the Bohemian Forest (rather flat catchments on metamorphic or granite rock with a large portion of peatland) ~~has~~had larger groundwater contributions than catchments in the Western Carpathians (more steep catchments on flysch). Nevertheless, the potential influence of basin attributes on catchment storage and runoff generation needs to be further investigated. The relative fraction of groundwater in streams is sensitive to inter-annual variation in snow storages, as also shown by Carroll et al. (2019). Similarly, the dynamic groundwater storage maybe correlated with elevation, indicating the relation between the groundwater storages and snow storages (Staudinger et al., 2017).

4.3 Influence of snow storages on summer baseflow and deficit volumes

Inter-annual variations in snow storages also affected summer baseflow, which is, additionally to spring snowmelt, related to summer precipitation and evapotranspiration. Our results showed that less snow led to lower snowmelt contribution to total runoff and to lower spring groundwater recharge with larger differences for catchments with higher S_f. These results correspond to other studies (Carroll et al., 2019; Cochand et al., 2019; Meriö et al., 2019). However, it does not necessarily mean that summer baseflow and potentially low flows are lower as well, since both the baseflow and low flows are more influenced by other water balance components, such as precipitation and evapotranspiration during spring and summer (Floriancic et al., 2019; Jenicek et al., 2016). Since the baseflow is a major runoff component during low-flow periods, it can be used as an indicator showing the potential extremity of such periods. Our results showed that snow-rich years produced higher summer baseflow in our study catchments. This indicated that spring snowmelt increased groundwater storage. Although the lower baseflow does not mean that potential low-flow periods are more likely to occur, it indicates that if the low-flow period occurs (e.g. due to lack of summer precipitation and/or high A_{ET}), the minimum streamflow might drop to lower values.

The results shown in Fig. 5 indicated that larger catchments with larger elevation ranges have more complex behaviour, especially in case of summer baseflow and deficit volumes. The impact of snowfall fraction (and thus snow storages) on summer baseflow and deficit volumes is less obvious or not present in these catchments, most likely due to the effect of higher A_{ET} in lower parts caused by higher air temperatures. Therefore, the snow is less important for summer runoff and low flows in such catchments.

The above effect of large area and elevation range could also explain the fact that the relationship between snow storages and summer runoff may be better explained by snowfall fraction rather than elevation. Although the snowfall fraction significantly increases with mean catchment elevation in our study catchments (Pearson correlation coefficient is 0.53, p value<0.001), the correlation coefficient might be influenced by the fact that mean catchment elevation cannot describe the hypsography of individual catchments.

Although in most of the catchments the summer precipitation was more important for summer baseflow, in some catchments with the highest snowfall fractions and larger proportion of area located at higher elevations, the winter snowpack was probably of a similar importance ~~as~~to the summer precipitation. An important implication for the future climate is that the summer baseflow might be lower because of lower snow storages even when summer precipitation would not change. The snow as the dominant mechanism controlling summer low flows was also proved by Meriö et al. (2019) for Finnish catchments with snowfall fractions higher than 0.35. Similar to the mentioned study, we also discovered some regional differences between our study catchments. For example, for catchments in the Eastern Sudetes and Western Carpathians, summer precipitation dominated the summer baseflow despite relatively high snow storages. This might indicate that those catchments had a shorter "memory effect" of snow to influence the runoff. Thus, the water exchange is faster in these catchments resulting in shorter residence times. Our results did not provide possible reasons for such behaviour, but differences in climate ~~regime~~regimes (increasing continentality from west to east), geology (flysch in the Western Carpathians vs. metamorphic or granite rock in other regions) and morphology (higher slopes in the Western Carpathians) could provide some explanation, as shown by several authors ~~in~~for other regions (Floriancic et al., 2018; Li et al., 2018; Staudinger and Seibert, 2014). However, more detailed research would be necessary.

Nevertheless, understanding how snow storages in snow-poor and snow-rich years influence summer baseflow and deficit volumes is always limited due to different meteorological conditions in individual years. For example, winter seasons in years with lower snow storages were also warmer and dryer, which could affect summer baseflow and low flows. However, despite these differences in winter precipitation and temperatures, summer precipitation, summer air temperature and summer A_{ET} were almost the same for both snow-poor and snow-rich years. This ~~indicated~~suggests that differences in summer runoff signatures can be related to changes in snow storages and spring groundwater recharge.

4.4 ~~Snow~~Snowfall-rain transition and potential future impacts

The results related to catchment response in snow-rich and snow-poor years indicated important potential consequences for annual and seasonal runoff and deficit volumes, which might decrease (or increase, for deficit volumes) in the future when the decrease in snowfall fraction is expected. However, the hypothesis highlighting the importance of snowfall fraction ~~on~~for runoff amount cannot be fully proven by splitting the study period into snow-poor and snow-rich years, due to the fact that snow-poor and snow-rich years differed not only in snow storages, but also in other meteorological signatures (as explained in ~~the~~ Section 4.3). Therefore, this runoff volume decrease was proven by a modelling experiment simulating the progressive change from snowfall to rain leaving the total precipitation, air temperature and P_{ET} unchanged. This way, we were able to separate the effect of changing snow to rain from other water balance components. A similar approach, using the same model and parameters (but for different purposes), was applied also by Jenicek et al. (2018).

The changes in runoff due to snowfall-rain transition as simulated by modelling experiments pointed at two different aspects; 1) changes in annual water balance and 2) changes in seasonal runoff distribution. The first aspect is demonstrated by results of ~~this~~the hypothetical experiment which showed an increase in ~~both~~ annual ~~and summer (JJA)~~ runoff for all 59 catchments. A closer look at the results suggests that the model simulated lower snowfall and thus snow storages that melted earlier. Due to more days without snow cover, the total annual A_{ET} increased (A_{ET} is calculated for days without snow cover in the model) which caused a decrease in total annual runoff. It means that the increasing ~~the~~ contribution of liquid precipitation to total runoff cannot compensate for the lower contribution of solid precipitation ~~in~~to total runoff. Moreover, potential snow-rain transition in the future will be caused by an increase in air temperature, which was not changed in our modelling experiment. Therefore, the A_{ET} might be even higher due to ~~a~~the temperature increase (in the case of enough available water). Consequently, annual runoff will likely decrease even more than indicated by our experiment. However, we are aware that this particular result may be affected by the model structure which describes the whole rainfall-runoff process in a simplified way, and thus the real catchment behaviour might not be captured correctly.

The second aspect, changes in seasonal runoff distribution, was caused mainly by lower snow accumulation for lower snowfall fractions (more rain than snowfall) and by earlier snowmelt. This widely influenced the timing of groundwater recharge and thus spring and summer streamflow, low flows and deficit volumes (Fig. 8b-d). In contrast to the decreasing annual runoff due to decreasing snowfall fraction, the increase of summer deficit volumes was simulated only for 58% of the study catchments. The remaining catchments did not show a clear trend or they behaved in the opposite direction. This suggested more complex behaviour of these catchments, which is probably caused by their location rather at lower elevations, and thus lower snow storages. Therefore, other climatic variables and catchment properties, such as geology and related groundwater storages might be more important than snow storages. However, more research would be necessary to find a detailed explanation. Nevertheless, the results from modelling experiments are consistent with analyses based on snow-poor and snow-rich years. Similar results ~~as~~to those for summer deficit volumes were achieved also for the number of days with deficit volumes, which also increased when snowfall fraction decreased. The described changes in seasonal runoff distribution are, in our opinion, more important (although expected) since they widely determine the water availability during the warm period when the water demand is generally higher (for vegetation growth, agriculture, hydropower production etc.).

Although our results may not be easily generalized since they are limited to the specific region, the decreasing annual runoff in the case of a precipitation shift from snow to rain ~~showed~~suggests that this shift in the precipitation phase will change the catchment behaviour such that less water might be available for summer runoff in the future. The lower annual runoff might be critical for water supply and water reservoir management (Brunner et al., 2019). For the seasonal water balance, it will therefore be important to understand whether the future increase in winter precipitation predicted by climate models for the region of Central Europe can compensate for the expected future reduction ~~of~~in the snowmelt component.

5 Conclusions

We found that 17~~-~~–42% (26% on average) of the total runoff in our selected study catchments originates as snowmelt ~~on average~~, despite the fact that only 12~~-~~–37% (20% on average) of the precipitation falls as snow~~.~~ (Fig. 3). It also seems that the difference is increasing at higher elevations with higher relative importance of snow ~~on~~for runoff regime. This particular result ~~proves~~suggests that snow is more effective in generating catchment runoff compared to liquid precipitation. This might have an important impact on water availability in the case of a future decrease in snow.

The mentioned difference between snowfall fraction and snowmelt runoff fraction was also documented by modelling experiments which showed that total annual runoff decreased in the case of a precipitation shift from snow to rain, even in the case where the total amount of precipitation and P_{ET} remained unchanged~~.~~ (Fig. 8). This might imply lower annual catchment runoff in the future when a precipitation shift from snow to rain due to air temperature increase is predicted by climate models. In general, snow-poor years ~~are~~were clearly characterized ~~with~~by lower snow runoff contribution to total runoff compared to snow-rich years in the analysed period 1980-2014~~.~~ (Fig. 5). Additionally, snowmelt started earlier in these snow-poor years and influenced the runoff for a shorter period compared to snow-rich years. Snow-poor years generated lower annual groundwater recharge and annual runoff compared to snow-rich years despite similar annual precipitation and A_{ET}, which resulted in mostly higher deficit volumes.

Inter-annual variations in snow storages also affected summer baseflow, which is, besides snow, related to summer precipitation and evapotranspiration. For most of the catchments, the lowest summer baseflow was reached in years with both relatively low summer precipitation and snow storage~~.~~ (Fig. 7). This showed that summer low flows (directly related to baseflow) are not only the function of low summer precipitation, but they are significantly affected by the previous winter snowpack. Although the summer precipitation is usually the most important climatic factor ~~to control~~controlling the summer low flow, the decrease in snow and earlier snowmelt might intensify the future summer low flows in ~~the future~~mountain catchments when generally less snow is expected.

Modelling experiments ~~performed in this study using the HBV model opened further questions related to model structure and parameterization, specifically how individual model procedures and parameters represent the real natural processes. An understanding of potential model artefacts might be important when using HBV or similar bucket-type models for impact studies, such as modelling the impact of climate change on catchment runoff.~~

~~Results~~ indicated that the future ~~higher liquid precipitation will not compensate the lower solid precipitation which~~decrease in snowfall fraction together with changes in seasonal runoff distribution might result in lower annual runoff~~.~~ despite no changes in total precipitation (Fig. 8). The lower annual runoff might be critical for water supply and water reservoir management. For the seasonal water balance, it will therefore be important whether the future increase in winter precipitation predicted by climate models for the region of Central Europe can compensate for the expected future reduction ~~of~~in the snowmelt component.

6 Data availability

Meteorological and hydrological data ~~to calibrate~~for the calibration of the HBV model were obtained from the Czech Hydrometeorological Institute (contact person: Ondrej Ledvinka, ondrej.ledvinka@chmi.cz). The HBV model outputs are available from the first author upon request.

7 Author contribution

MJ initiated the study, developed the methodology and performed all analyses. OL prepared input meteorological and hydrological data used to calibrate the HBV model. MJ prepared the manuscript with a contribution from OL.

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

Support from the Czech Science Foundation (project no. 18-06217Y, Influence of seasonal snowpack on summer low flows: climate change implications on hydrological drought) is gratefully acknowledged. Meteorological and hydrological data ~~to calibrate~~for the calibration of the HBV model were obtained from the Czech Hydrometeorological Institute (contact person: Ondrej Ledvinka, ondrej.ledvinka@chmi.cz). Many thanks are due to Tracy Ewen for English corrections.

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