Authors’ final response to interactive comments of the Referees

Black text: Referee comment

Blue text: Authors’ final response

Author’s technical comment: Please note that we created new figure (newly Fig. 2) which replaced original Table 3. Thus, figures and tables numbering used in the revised version as well as in our final response differs from numbering used in original manuscript. The changes of numbering are also highlighted when referring to specific figure.

Firstly, we thank both reviewers for the many valuable comments and suggestions to improve our contribution. We want to highlight new analyses which has been made and included to the revised version of manuscript. These analyses consider some comments of both referees and thus we put their description in front of point-by-point responses introduced below.

1. As announced in responses to both referees, we extended analysis of changing effect of maximum SWE and minimum discharges using weekly Theil-Sen slopes (Fig. 4 in original version of manuscript, newly Fig. 5) by including dates of melt-out (snow-free dates). The melt-out date was calculated from SWE data for each catchment and year. The procedure was described in the section 2.3 of revised version (see manuscript with marked-up changes). Consequently, Fig. 5 was modified in order to display melt-out dates which enables better interpretation of the memory effect length (how long the snowmelt affects runoff after melt-out). Longer snowmelt contribution to minimum discharges in higher elevation catchments is clear even when consider different date of melt-out (black points and whiskers in Fig. 5). Analysis mentioned above was done both for complete observation period and when only dry preceding conditions were considered. This enabled to assess the catchment sensitivity also when liquid precipitation in the warm period is below average. No figure from this specific analysis was included in the manuscript (the differences to Fig. 5 are rather minor), but all results are described in section 3.2 of revised version.
2. We did additional analysis of relations between predictors and response variables in order to better describe the differences between catchments. In the original manuscript, these relations were analyzed using Spearman rank correlation coefficients and shown in Table 3 and described in the section 3.1. However, Table 3 did not allow a detailed look at differences between catchments (all catchments were analyzed as a one set). Thus, we decided to remove the original Table 3 and replace it with a new figure (Fig. 2) that displays heatmaps showing Spearman rank correlation coefficients for all predictors and response variables separately for three elevation groups. Dendrograms were used to show clusters of similar predictors and response variables. Additionally, the melt-out date was added as a new predictor. The new Fig. 2 improved the interpretation of changing influence of predictors both in time and at different elevations. Additionally, Fig. 2 shows the suitability of individual predictors to describe the variability of low flows (such as the difference between maximum SWE and winter precipitation as mentioned by the Referee #2) in a clearer way. As a consequence, section 3.1 and respective parts in the discussion (section 4.4) were completely rewritten (see revised manuscript with marked-up changes).
3. We modified Table 3 (former Table 4) by including drainage density as a catchment property (suggested by Referee #1). We found a significant correlation between the drainage density and the low flow sensitivity in summer to the change of maximum SWE

(Table 3). The findings from this new analysis are described in the section 3.2 of the revised version.

4. Many parts of original manuscript were largely rewritten in order 1) to better highlight the novel findings resulting from analyses and 2) to improve the readability of text which we believe is now more helpful for the reader. This included abstract, introduction, methods, results, discussion and conclusions.
5. Additionally, we modified most of the figures as suggest by both referees and Michael Stölzle in his short comment. All changes are described in the "Modification of figures" section in this document.

Major comments of the Referee #1

Jenicek and colleagues present a data driven study, which uses climate and runoff data to study the effect of snow storage and precipitation on summer low flows for 14 catchments in Switzerland. The main findings of the paper are (i) maximum winter snow accumulation influenced summer low flow, but is not the only controlling factor, (ii) in years with below average precipitation amounts during spring and summer the importance of snow accumulation increased, (iii) the sensitivity of summer low flow to snow accumulation is higher in high elevation catchments. Although understanding the role of (changing) snow conditions on summer low flows is a relevant topic for HESS I do have some serious concerns about the current version of the paper, and the papers needs to be significantly improved before this paper can be considered for publication in HESS:

1. I am not sure if the findings of the paper are significantly novel, or if they provide useful new insight in the role of snow for summer low flow conditions, because the analysis only relies on statistical relationships between snow conditions and summer low flow conditions but does not provide any mechanistic explanations of the relationships you describe. The statistical findings by itself (in my opinion) only confirm some obvious qualitative findings that are not surprising: the fact that (i) maximum winter snow accumulation influenced summer low flow, but is not the only controlling factor is not surprising, and differences with for example Godsey et al. [2014] are not really surprising either if you consider the strong Winter dominated precipitation regime of the Western US compared to more constant (and even sometimes summer dominated) precipitation regimes of Switzerland. Also finding (ii) in years with below average precipitation amounts during spring and summer the importance of snow accumulation increased only seems obvious to me, similar to (iii) the sensitivity of summer low flow to snow accumulation is higher in high elevation catchments because in these catchments snow is a higher fraction of the total water balance of the catchment (compared to rain) thus a % change in snow is likely to lead to a larger % in runoff (if all other factors are the same). I do not argue that results of empirical analyses are only valuable if they confirm some unexpected, but I do think there is some novelty lacking in this paper as I don't see how the paper really provides new understanding, refined previous understanding, or helps with better prediction of summer low flow conditions in Switzerland. Thus, I would recommend the author's to (i) either write the manuscript such that novel contributions are better highlighted where you show how we really improved our understanding of ability to predict, or come up with some additional analyses that would allow this.

   We agree, that most of findings are not surprising as they mostly support our existing qualitative knowledge of how snow contributes to summer runoff. However, we believe that the quantification of snow importance is a valuable and novel contribution. We also argue that the findings are still important even if they do not change our process understanding. Additionally, results of this study indicated regions which might became more vulnerable to drought occurrence in the future because of decrease of snow accumulations and snowfall fraction during cold period. We benefit from recently generated SWE data sets which, in our opinion, significantly improved presented analyses.

The referee suggested to "(*i) either write the manuscript such that novel contributions are better highlighted, or (ii) come up with some additional analyses that would allow this*."

We combined both of mentioned recommendations in the revised version of manuscript. Please, see our final response at the beginning of the document which introduces all major analyses and changes which has been made in the revised version. Additionally, see the final response to major comment 3 focusing on catchment properties.

2. You choose at set of 8 predictors for summer low flow conditions. Maybe the choice of indicators is obvious for you, but clarify why you chose them.

   We agree, that the explanation was missing in the original version of manuscript. We clarified this in the methodology part of revised version (section 2.3 "Statistical analysis and assessment", 3rd paragraph). The advantage of this choice is that only SWE, precipitation, air temperature and runoff data are needed for the calculation of all predictors. These data are often available also for other regions which enables to test our results also elsewhere with possible transfer to ungauged catchments.

3. You state that "maximum winter snow accumulation influenced summer low flow, but could only partly explain the observed inter-annual variations. One other important factor was the precipitation between maximum snow accumulation and summer low flow". Although I agree with statement, I think the manuscript lacks a more thorough discussion of other factors that can explain low flow conditions. As an example, what about evaporation differences between years? They are a major component of you catchment's water budget, affect water storage (and thus low flow conditions), but are completely unmentioned. Or what about the role of landscape draining properties (e.g. Tague et a., [2004])

   We agree that our results presented in this study do not fully explain the process causality. It means we are not able to precisely explain possible reasons of relations shown in our results. We just explored the dependencies and quantified them for different catchments. It means, we are able to estimate how sensitive the catchments are to any change of winter snowpack but process-based understanding at the catchment scale is limited and has to be further investigated. Still, we give partial explanation related to catchment properties, namely elevation, size, slope, drainage density, S/P and maximum SWE (Table 3 in revised version of manuscript).

   In the revised version, we modified Table 3 (former Table 4) by including drainage density as a catchment property. We found significant correlation between the drainage density and the low flow sensitivity in summer to the change of maximum SWE (Table 3). Findings resulting from this new analysis are described in the section 3.2.

   In this study, we did not do a thorough analysis of potential and actual evapotranspiration because of a lack of available data. However, water balance component estimates for the entire Switzerland during the last 100 years show that annual precipitation and runoff vary far more than evaporation (Hubacher and Schädler, 2010). So we expect that variations of ET from year to year are relatively minor compared to changes in SWE and if there are any, than we would expect more actual evapotranspiration in wet years and less in dry ones. This feedback leads to the hypothesis that actual evapotranspiration is less useful as predictor for low flows. The ET changes were not discussed in the original version of manuscript so above mentioned explanation was included in the discussion section 4.1.

   Additionally, the discussion section 4.1 was largely modified to better focus both on catchment properties (elevation, slope, drainage density etc.) and meteorological properties (including evapotranspiration).

4. The analysis is based on catchment average values and the catchment divided into two parts. Is this strongly limiting your analyses for a catchment larger than 1500km^2?

   We are aware that using catchment means in catchments with different size can make the interpretation more difficult. However, we decided to do the analysis for entire catchment scale (but not for large basins). Thus, we used both SWE calculated as a catchment mean and SWE calculated from higher situated 50% of catchment area. We assumed, that snow in higher elevation could be more important for summer low flows. However, both approaches brought nearly identical results (see Fig. 2 and related parts of the section 3.1 in the revised version of manuscript). Additionally, Spearman rank correlations are not significant when looking on the effect of catchment size on catchment sensitivity to SWE decrease (Table 3). On the contrary, we cannot exclude the effect of size in very large basins (except Hinterrhein, all studied catchments are smaller than 800 km^2). Including larger catchments is not feasible, as the larger catchments in Switzerland are significantly affected by hydropower regulation. All findings and the explanation mentioned above were better highlighted in the section 3.2 of revised version.

5. I have difficulty to efficiently read the results section. The section refers to the graphs and tables but does not explicitly takes the reader by the hand in explaining what part of the graph we should focus on when you conclude anything from these graphs.

   Thank you for this comment. As mentioned in the final response at the beginning of this document, many parts of the original manuscript were largely rewritten. One reason was to improve the readability of the text. We believe, it is now more helpful and clearer for the reader.

Major comments of the Referee #2

I reviewed the paper “Importance of maximum snow accumulation for summer low flow in humid catchments” by Jenicek et al. Overall, I am quite intrigued by this topic, hence my reason for reviewing the paper. However, I found the paper lacking a clear takehome message and was often confused by the writing and organization of the paper.

The authors lay out two interesting research questions: 1) determine the length of memory effect on low flow conditions for maximum SWE and 2) estimate the sensitivity of catchments to changes in snowpack. While I find these questions compelling they don’t seem to be very well answered by the study (see major comments below). In particular, the authors seem to neglect discussing the very high correlation between low flows and winter precipitation (almost always explaining more variability than maximum SWE). I think this may be an opportunity, rather than a limitation, to identify a novel response (see major comments). Shifting the study questions to better reflect the [potential] novelty of the work is needed. Secondly, I do not feel that the authors adequately address their second question about sensitivity to changing snowpacks. They seem to suggest that high elevation catchments are as much or more sensitive to warming as low elevation catchments. This seems like a large simplification (see major comments below). I lay out several potential ways to reframe the work that may help address its novelty.

We agree, that most of findings are not surprising as they mostly support our qualitative existing knowledge of how snow contributes to summer runoff. However, we believe that the quantification of snow importance in selected area is a valuable and novel contribution and that the findings are still important also if they don’t bring any change of our process understanding. Additionally, we benefit from recently generated SWE data sets which, in our opinion, improved presented analyses. Below, we provide answers to major comments of the reviewer. Because we found several valuable comments in the reviewer’s text, we used sub-headers to separate the individual issues.

Novelty of the work: To me the important questions for a climate like Switzerland are 1) does changes in the timing of snowmelt or changes from winter snow to rain alter summer baseflow? and

2) can summer precipitation counteract the effects of changing winter precipitation inputs? The paper currently feels like it is arguing that SWE is more important than precipitation (which is not supported by the results) and that SWE becomes more important during dry summers (which is really not surprising). From my perspective the real question is does SWE (timing or amount or S/P) explain additional variability in low flows beyond what winter precipitation explains. This may require a different analysis, possibly normalizing for winter precipitation or some type of step-wise regression. One might hypothesize that snowpacks release water later in the year, so the timing of snow disappearance may be the critical information (in addition to winter precip amount). Currently, the paper suffers greatly by not discussing that winter precipitation explains as much or more variance of low flows than SWE variables (Table 3). I also suggest that the authors use wet and dry summers to ask when summer precipitation can overcome poor snowpacks or dry winters. Perhaps this could be accomplished using an elasticity type relationship for both summer and winter precipitation and SWE. Do you need more summer precipitation to drive the same low flows that winter precipitation (i.e. winter precipitation is more efficiently partitioned to streamflow)? This is an important question that has large climate change impacts. Along those same lines, I strongly encourage the authors to move away from their second research question about sensitivity to changing snowpacks unless they significantly bolster related analyses (see comment below). This is a great discussion point, but currently poorly addressed.

Research questions

We thank the reviewer for suggestions to modify the research questions. We do believe that there are still many interesting questions and issues related to the topic which are currently not fully answered and should be definitely investigated in the future. The drought occurred in central Europe this year is a good reason for further research of this topic.

We worked towards *1) quantifying how long snowmelt affects runoff after melt-out and 2) estimating the sensitivity of catchments with different elevation ranges to changes in snowpack.* Referee expressed certain doubts if these goals were fully addressed in the original manuscript. We hope that the additional analyses presented in the revised version of manuscript could dispel these doubts. All new analyses (focused both on "memory effect" and catchment sensitivity) are described at the beginning of this document. Additionally, many parts were largely rewritten in order 1) to better highlight the novel findings resulting from analyses and 2) to improve the readability of the text which we believe is now more helpful for the reader.

Combined effect of snow and precipitation

We do not intend to argue that SWE is more important than precipitation (this is really not supported by our results). Due to moderate humid climate in Switzerland with precipitation almost equally distributed in a year (opposite to western US), the aim was to show the combined effect of snow and liquid precipitation and their changing role in time (in different months) and in catchments with different elevation. Additionally, we wanted to quantify the effect of snow on minimum discharges when liquid precipitation is below average (or opposite, when SWE is below average) as documented in Fig. 8 of revised version. This could increase the reliability of predictions of minimum discharge during summer as newly mentioned in the section 4.4 "Practical use of a quantification of snow influence on summer low flows" of revised version (this section was newly added to the revised version). To clarify this point, we significantly modified the discussion section 4.3 (last paragraph).

Timing of snow disappearance

We agree that timing of snow disappearance in specific catchment represents critical information (as also mentioned by the Referee #1). So we did a new analysis, focusing on the "memory effect" of individual catchments. We included date of melt-out (snow-free date) as a new predictor to better describe the "memory effect" of catchments. Please see our final response at the beginning of this document which describes this in more detail. Exact procedure is described in the section 2.3, results are shown in Fig. 5 (former Fig. 4) and section 3.2 of revised version.

Wet and dry years

The separation to wet and dry years (both in terms of SWE and liquid precipitation during warm period) was already used in the original version of manuscript. The Fig. 8 (former Fig. 7) shows this separation.

Additionally, the procedure used to create Fig. 5 (former Fig. 4) was repeated both for complete observation period and when only dry preceding conditions were considered. This enabled to assess the catchment sensitivity also when liquid precipitation in the warm period is under its average. There is no figure resulted from this specific analysis (the differences to Fig. 5 is rather minor), but all results are described in the section 3.2 of revised version.

Winter precipitation

In original version of manuscript, we used winter precipitation as a predictor and we expected similar results as with maximum SWE. Winter precipitation (from November to April) is highly correlated with SWE and we expect increasing mutual correlation for higher elevation catchments with higher S/P. Despite higher correlations (Table 3 in original version), we consider winter precipitation to be less suitable as a predictor than maximum SWE. One of the reason for this is that winter precipitation is not corrected for undercatch of snowfall. Thus, we expect larger errors varying between stations according to site conditions and wind speed. This explanation was not provided in the original version of manuscript, thus we put it to the discussion section 4.4 of revised version.

As described in final response at the beginning of this document, we did new analysis of relations between predictors and response variables in order to better describe the differences between catchments. We created hetmaps (new Fig. 2) showing Spearman rank correlation coefficients for all predictors and response variables separately for three elevation groups. This new figure enabled better description of suitability of individual predictors to describe the variability of low flows (such as the difference between maximum SWE and winter precipitation). The maximum SWE (both averaged per catchment and in upper 50% of the catchment area) was in most cases the best predictor for higher elevation catchments during summer (July and later). Additionally, maximum SWE and the sum of new SWE were better predictors than winter precipitation in snow dominated catchments to predict the number of days with low discharge (No. days < Q25%). On the contrary, winter precipitation was a better predictor than maximum SWE for lower elevation catchments (June to September) and for middle elevation catchments during spring (May, June). Since our focus was primarily on middle and high elevation catchments and summer months, maximum SWE seems to be the best predictor, although differences are not large.

Findings related to differences in predictors and response variables are described in the section 3.1 which was completely rewritten.

Climate change effects are oversimplified: The authors use elevation as a means to organize the catchments and their sensitivity to SWE. This seems problematic given that there is generally a large gradient of precipitation and S/P ratios across elevation. The discussion seems to imply that high elevation catchments are as much or more sensitive as low elevation catchments. This may be true if catchments are all near zero degrees and precipitation is evenly distributed across the winter, however, this is not discussed. I can imagine situations where high elevation catchments are less sensitive to a given amount of warming because they are well below 0 C for most of the winter. Given that the authors do not partition variance well between winter precipitation and SWE effects on low flows, I think the discussion of climate change is very weak. It is quite possible that the points suggested above may improve discussion points here, however, I suggest the authors do not make that a central research question but a discussion point (or significantly bolster the associated analyses).

Discussion of climate change

The insufficient discussion of climate change effect was mentioned by the other reviewer as well. Thus, the discussion section related to the climate change (part 4.2) was largely modified in the revised version. Instead of discussion toward climate change (which was not in the scope of this paper), it goes more towards the role of the changing snow conditions. Thus, the title was modified as well. Additionally, section 4.2 discusses the uncertainty arising from using mean catchment elevation instead of more detail representation of catchment elevation (using elevation ranges, for instance).

Catchment sensitivity

We do not argue that higher elevation catchments are more sensitive to low flow occurrence in all circumstances. Based on our results we can only quantify the potential decrease of minimum discharges in case of decrease of maximum SWE. We did not explore relations between possible warming in the cold season and minimum discharges in the warm season (although some indirect evidence of this could be found in Fig. 2 using predictor named "sum of positive air temperature"). We do not know if this SWE decrease will occur. However if it happens, than the same percentage SWE decrease in higher elevation catchments will results in stronger percentage decrease of minimum discharges (see Fig. 6 in revised version showing the elasticity). Additionally, different sensitivity to drought in catchments with different elevations was also described by Staudinger et al. (2015) who made similar conclusions. We agree, that this was not clearly written in the original text so we put mention explanation to the discussion section 4.2 of revised version.

Findings showing the catchment sensitivity which are displayed in the Fig. 4 and 6 (former Fig. 3 and 5) were described in the section 3.2 of revised version in more detail. Together with findings resulting from Fig. 2 (heatmaps) we believe that we better addressed the research question dealing with the catchment sensitivity. However, we are aware that our results could only partly answer these questions and we think this needs to be investigated in the following research.

Use of monthly/weekly low flows: I am mixed about the use of monthly/weekly low flows. On one hand, this fits with the question about memory effects on low flows that the authors pose. It also gets around potential issues with noisy annual low flow data. On the other hand, what is a low flow in May and why does anyone care? I find the use of the lowest summer flow as a much more compelling response variable to predict. The use of monthly low flows is particularly problematic early in the summer when some watersheds are storing water as snow and others are not. In some ways the current effort is quantifying the recession relationship of the watersheds, which is [in my opinion] not the focus of the paper. Perhaps I am missing something here that could be better explained in the text.

Monthly/weekly low flows

Clearly we see the lowest summer flow as a compelling response variable, given the water management interest and possible issues connected to it. However, for the development of the role of snow compared to liquid precipitation this one response variable is not sufficient. We agree that the mixing of monthly/weekly data could lead to some confusion. We think that monthly approach is sufficient for most analysis we did. However, for memory effect calculation we used weekly data which enabled to see slowly decreasing effect of snow on minimum discharges (see Fig. 5 in the revised version). We agree that mentioned explanation was missing in the original version of manuscript, so we added it to the discussion section, part 4.3 of revised version. Additionally (as discussed above), we included melt-out days to improve the interpretation of the catchment's memory effect.

Starting day of low flow analysis

We chose the period from May to September to show the changing importance of snow contribution to low flows in different catchments, both in lower and higher elevations (melt-out occurs usually in early April in lower elevation catchments of our selection). We believe that this is helpful especially when looking on Fig. 3 and Fig 5 in the revised version of manuscript. We also tested the effect of snow on summer minimum discharge (June-August, not shown in the paper). The results for most of catchments were very similar to existing relations calculated for August as most of summer (June-August) minimum discharges occurred in August. This was also the reason why we chose a monthly/weekly step. We agree that mentioned explanation was missing in the original version of manuscript, so we added it to the discussion section, part 4.3 of revised version.

Minor comments of the Referee #1

Abstract Line 3: It isn't really "winter" precipitation that is sensitive to temperature changes, which implies a 3-month season, but rather something like "cold season".

We agree. We changed "winter" to "cold season".

Lines 3-4: "snow" does incorporate both "snowfall" and "snow storage"?

We agree. We changed "snow" with "snow storage".

Line 4-5: Does it necessarily relates to "groundwater" recharge as water in some catchments may mostly only reach the unsaturated zone?

We understand the point, although this is only general information. We changed the sentence to "...will affect soil and groundwater storages" to be clearer.

Line 8: Instead of "snow", be specific if you mean "snowfall", "snowpack" or both.

The sentence was modified as follows: "*We worked towards 1) quantifying how long snowmelt affects runoff after melt-out and...*".

Line 21: since you haven't defined the elasticity index it is difficult to interpret your statement by just reading the abstract.

We think, the elasticity should be generally known as it is often used in many studies (mainly climate studies). However, we modified the sentence as "*We assessed the sensitivity of individual catchments to the change of maximum SWE using the non-parametric Theil-Sen approach as well as an elasticity index*". This should refer to the information that elasticity describes sensitivity of catchments.

Introduction (7025), Line 2-3: Is "The shift from snowfall to rain" one of the most important effects of predicted climate change "in general" (as you currently state) or "on the hydrological cycle".

We agree. We added "..on the hydrological cycle" to be clearer.

Line 9: The reference of Berghuijs et al [2014] studies inter-annual and mean-annual water balances and only speculate what the changes in seasonal hydrology could be. Hence the reference is not really appropriate here. Also, please be specific with what you mean by "might influence"; e.g. modelling results indicated that ....

We agree. Reference Berghuijs et al. (2014) was replaced with Godsey et al. (2014) who explored the effect of SWE on summer minimum discharges. Formulation *"...will affect groundwater recharge during spring and might influence..."* was changed to *"...will affect groundwater recharge during spring and as a consequence also low streamflow values..."*.

Line 10-21: There are clear differences between the findings of the reduced snow days in Switzerland (mainly in spring) and western US (mainly in Winter). It might be good to highlight that more explicitly.

The decrease of S/P in winter (January) in the US is typical for the West Coast with generally higher air temperatures during winter than in the rest of study area. This information was newly added into the text.

Introduction (7026), Lines 8 - 12: Since studies find regional differences in the streamflow trends, do they also have different physical explanations, and are these explanations relevant to mention?

Studies mentioned in this paragraph were selected just to document regional differences in streamflow trends. As some of these studies tried to explain differences within a studied region (Birsan et al. 2005; Fiala et al. 2010), physical explanation for differences between regions is not clear (could be e.g. due to increasing continentality from west to east direction in Europe). However, we didn't change the text since the physical explanation is not fully clear from mentioned studies and it would be rather speculative.

Line 15: "above 1000ma.s.l. and below 2500" or "between 1500 and 2500 m.a.s.l"?

We agree. We reformulated it as: "*between 1500 and 2500 m a.s.l*".

Line 16: Can you be more specific than "more sensitive"? Was it a large or small difference? Does this still focus on mean runoff?

We added more information related to the study for clarity. The exact quantification was not presented in the paper since the sensitivity was expressed based on proposed similarity measures (level of agreement) typically ranging from 0 to 1 (Speich et al. 2015). It means only relative comparison was done by Speich et al. (2015).

Line 26-28: "However, the ... al., 2015)." Rewrite the sentence such that it reads well and that it is clear if you made up a statement yourself or it is based on a reference.

We modified the sentence to be clearer as: "*However, snow cannot solely explain the sensitivity to drought, although higher elevation catchments in the Swiss Alps were found to be less sensitive to drought origin (Staudinger et al., 2015). Additionally, some modelling experiments suggested larger groundwater storages in higher elevation Swiss catchments which may additionally explain the lower sensitivity of higher elevation catchments to low flows (Staudinger and Seibert, 2014)*"

Introduction (7027), Line 3: Specify this is the Sierra Nevada in the US (and not Spain, or Colombia).

We added "*in the western USA*".

Line 7: Unclear what a "longer memory effect" exactly means. It is important to make this clear as this is also mentioned in your objectives of the study.

We modified the sentence and we changed also the paragraph with objectives of our study as: "*In this study we want 1) to quantify how long snowmelt affects runoff after melt-out and 2) to estimate the sensitivity of the catchments to changes in snowpack.*"

Line 16: what about spring precipitation?

We agree. We modified the sentence as: "*Our study adds to earlier studies, by focusing on the combined effect of snow and liquid precipitation during the warm period and its varying importance for individual catchments.*"

Line 17: I do not see how you look at their spatial influence. Do you mean between catchment differences?

Yes, with spatial influence we mean the differences between investigated catchments in different elevations. We modified whole sentence as described in previous comment.

Lines 18-19: I don't think this statement is very clear "To explore ... amounts overall". Why is this more important here?

With this sentence we wanted to highlight the fact that majority of studies focusing on the effect of snow on summer minimum discharges have been made in regions with different precipitation patterns. The example is western US which is the region with different precipitation seasonality and lower total annual precipitation compared to Switzerland (humid climate where annual precipitation are more equally distributed during year and their total amount is considerably higher in some cases). We reformulated the sentence as: “*Exploring this combined effect is particularly important in humid regions where annual precipitation is approximately equally distributed over the year, while most studies were performed in climates with more seasonal precipitation and/or smaller precipitation amounts overall (such as in the western USA).*”

Study area, Lines 25-26: What do you mean by “as close as possible to natural conditions". Does this mean there are no land-use changes? Does it only refer to dams in the river?

We mean that streamflow is near-natural and no major human influences by dams, water transfer etc. are present. This information was added into the text by adding new sentence: “*Catchments as close as possible to natural conditions were selected, i.e. streamflow is near-natural and no major human influences such as dams or water transfer are present.*”

Page 7028, Line 22-24: Be more specific in what Jorg-Hess et al. (2014) already did regarding the link of SWE and low flows.

We modified the sentence as: “*Additionally, Jörg-Hess et al. (2014) used this SWE data to assess the influence of snow conditions on summer low flows for a large Swiss catchment with possible use for minimum spring and summer runoff forecast based on SWE as the only predictor.*”

Page 7029, Line 12: Clarify why you chose this set of predictors. Maybe it is very obvious, but you currently do not explain your choice

Please, see answer to major comment 2. The explanation mentioned in this comment was added to the manuscript (part 2.3 “Statistical analysis and assessment”).

Line 26: why did you set the threshold at 1.1C? Is this based on another study? Does the threshold affect your choice?

The threshold temperature near 1°C was used by several authors (Dai, 2008; Feiccabrino and Lundberg, 2008) who used data from stations where the information about phase of precipitation were available. Additionally, we tested different threshold temperatures, and found no sensitivity of our results on an exact value. This explanation was added to the section 2.3 “Statistical analysis and assessment”.

Page 7031, Line 2: What do you exactly mean by “is more obvious"

Thank you for this notice, the original sentence was really not fully clear. The sentence was modified in the revised version as: “*The higher the value, the steeper the slope of regression and thus the more sensitive is the dependent variable (e.g. minimum discharge) to the change of the independent variable (e.g. maximum SWE).* “

Page 7032: Section 3.1: be explicit which results of the table you use to make these conclusions.

The section 3.1 was completely rewritten (since we removed Table 3 and replaced it with a new Fig. 2 showing heatmaps). Please, see our final response at the beginning of this document for detail information.

Page 7034: Section 3.3 Explain why you use these three catchments?

We selected three snow-dominated catchments in high and middle elevations (as mentioned in the text) in order to show the effect of combined effect of snow and liquid precipitation. These catchments were selected as typical representatives. Although, there are some differences between all studied catchments in high and middle elevations, all of them show similar behavior. Therefore, to reduce the manuscript extent, we decided to show only three representatives. The first paragraph of section 3.3 was modified in the revised version in order to reflect mentioned explanation.

Discussion section: the discussion of the sensitivity to climate change is really short and does not include any effects different expected SWE changes between the different altitudes. In lower elevation catchments the % of SWE is much more sensitive to temperature changes, than high elevation catchments. This needs to be emphasized. Also, a statement as “This reduction might increase problems with water availability in affected regions" is not really helpful if you do not provide any numbers of changes you expect with for example a 2 degrees warming.

This point was mentioned also by second reviewer. The discussion section relating to climate change (part 4.2) was largely modified in the revised version. Instead of discussion toward climate change (which was not in the scope of this paper), it goes more towards the role of the changing snow conditions. Thus, the section title was modified as well.

I don’t learn anything from the the discussion section on “Combined effect of snow and precipitation".

This paragraph aimed to highlight that liquid precipitation could only partly overlay the effect of snow. Even in case of high liquid precipitation, the minimum discharge remains lower in case of low snow conditions in previous winter. The discussion section related to combined effect of snow and precipitation (part 4.3) was largely modified in revised version. New paragraphs related to this topic were added. Moreover, we add new section 4.4 “Practical use of a quantification of snow influence on summer low flows” which summarizes the potential for use our results for practical use.

Maybe to my ignorance but I do not understand the argument of using SWE since you don’t have groundwater data “Snow melt ... minimum discharge (Fig. 2)"

We agree. This sentence is not necessary in the result section and it was removed.

7039, Line 11: Be more specific than “significantly affected low flows". Does it change the volume of low flows, the timing of low flows or both?

This point summarized the different period by which snowmelt contributes to minimum discharge in catchments with different elevation (it means only timing is considered in this case). The sentence was modified to be clearer. Please, see “Conclusions”, bullet 1.

It is unclear if the statement “Low flows occurred later in the year for years with above average snow accumulations. A decrease of maximum snow accumulations by 100mm resulted in earlier runoff minima by 12 days" is applicable for all catchment?

This statement is valid for all selected catchments (on average) considering their mean day of minimum discharge occurrence. The sentence was reformulated. Please, see “Conclusions”, bullet 2.

Line 20-24: “Snow and ... were considered." It is unclear if the combination of rain and snowpack can sufficiently explain low flow conditions or if more information is needed.

We agree that the formulation was not fully clear in the original version. Even if consider both snow and liquid precipitation, there is still some portion of annual variability which cannot be explained by these two predictors. The sentence was reformulated in revised version to be clearer. Please, see “Conclusions”, bullet 4.

Figure 1: Does it make sense to also have the altitude differences in Switzerland indicated on the map?

This was also suggested in the short comment posted by Michael Stölzle. We added DTM as an additional information into Fig. 1.

Figure 2: I doubt this will be readable when printed on a A4 format.

Figure labels were enlarged. Additionally, we modified this figure in the way as suggested in short comment of Michael Stölzle (mainly unnecessary labels were removed). This figure is newly Fig. 3.

Figure 4: How do you explain the significant negative correlations?

We do not see any physical explanation for negative correlation and we consider them as a noise. Additionally, most of them are not statistically significant (0.05 level). Most probably, they indicates mixed effect of snow and liquid precipitation in the warm season. The explanation was added to result section 3.2 of revised version.

Figure 6: Make clear what the reference date is on the y-axis.

The day of year "1" represents the first day of calendar year (1.1) and day of year "365" represents 31.12. This information was added to the figure caption. This figure is newly Fig. 7.

Figure 8: Are the labels of this figure readable when printed on A4 format? Can you provide a color-scale for the elevation indication?

Figure labels were enlarged. Additionally, we modified color scale for elevation; only three elevation groups thus three distinct colors were used (as suggested by Michael Stölzle). Same color coding was used also for Fig. 6 and 7. This figure is newly Fig. 9.

Minor comments of the Referee #2

Abstract has no quantitative results

The abstract was modified and quantification was added.

Introduction seems to wander from idea to idea without a clear structure. Too many paragraphs that talk about similar ideas.

When writing the Introduction, we followed sequence "changes of SWE/winter precipitation (mainly due to climate change) – consequences to runoff changes – liability/sensitivity of different regions to described changes in snowpack". In the revised version, we made some changes in the Introduction in order to better specify selected ideas resulting from studies described. Some changes also reflect minor comments of the Referee #1.

I would like to see a table of the mean and CV of all predictor variables and response variables.

To get valuable information it would be necessary to specify all values separately for individual catchments and in case of response variables also for individual months (for instance, mean value of maximum SWE of all catchments as a one set do not tell much even if Cv is provided). Mentioned solution would result in a huge table (>500 values) which probably has to be placed as an appendix. So we decided to enlarge Table 1 and put most important values into this table (except those which were already there, we included drainage density, melt-out date and winter precipitation). However, we can provide the complete table if it would be requested by the Referee/Editor.

The figures are extremely hard to read in black and white, which many people will do when printed. Particularly Figure 4, 7, and 8.

The use of colors enables to provide the reader with additional helpful information (e.g. catchment elevation as it is in Figs. 6, 7 and 9 of revised version). Actually these days many readers will not print papers but read the pdfs at a computer or tablet, where color makes figures more readable. However, we did some modification (either we changed colors or we changed to black-white) as described in the following section "Modification of Figures" below.

Modification of Figures

Modification of Figures reflected comments of both referees and short comment of Michael Stölzle as explained below. The numbering reflect the revised version of manuscript:

Fig. 1: DEM was added into Figure.

Fig. 2: Completely new figure showing heatmaps and dendrograms of predictors and response variables for three elevation groups.

Fig. 3: Figure labels were enlarged. Additionally, we modified this figure in the way as suggested by short comment of Michael Stölzle (unnecessary labels were removed).

Fig. 4: The figure was not changed.

Fig. 5: The figure was largely modified according to results of new analysis (mainly the information about melt-out date was added into this figure).

Fig. 6: Figure labels were enlarged. Additionally, we modified color scale for elevation; only three elevation groups thus three distinct colors were used (as suggested by Michael Stölzle). Same color coding was used also for Fig. 7 and 9.

Fig. 7: Same color coding for elevation groups was used as in Fig. 6 and 9. Additionally, dots with min and max values were remove to be clearer.

Fig. 8: The figure was changed to black-white and unnecessary labels were removed.

Fig. 9: Figure labels were enlarged. Same color coding for elevation groups was used as in Fig. 6 and 7.

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Importance of maximum snow accumulation for summer low flows in humid catchments

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Abstract

The expected increase of air temperature will increase the ratio of liquid to solid precipitation during ~~winter~~the cold season and, thus decrease the amount of snow storage, especially in mid-elevation mountain ranges across Europe. The decrease of snow will affect soil and groundwater ~~recharge~~storages during spring and might cause low streamflow values in the subsequent ~~summer period~~warm season. To evaluate these potential climate change impacts, we investigated the effects of inter-annual variations in snow accumulation on summer low flow~~ and addressed the following research questions: (~~. We worked towards 1) ~~how important is snow for summer low flows and~~quantifying how long ~~is the "memory effect" in~~ snowmelt affects runoff after melt-out and 2) estimating the sensitivity of catchments with different ~~elevations? (2) How sensitive are summer low flows~~elevation ranges to ~~any change of winter~~ changes in snowpack~~?~~. To find suitable predictors of summer low flow we used long time series from 14 alpine and pre-alpine catchments in Switzerland and computed different variables quantifying winter and spring snow conditions. ~~We assessed the sensitivity of individual catchments to the change of maximum snow water equivalent (SWE_{max}) using the non-parametric Theil-Sen approach as well as an elasticity index.~~ In general, the results indicated that maximum winter snow ~~accumulation~~water equivalent (SWE) influenced summer low flow, but could expectedly only partly explain the observed inter-annual variations. On average, every decrease of maximum SWE by 10% caused a decrease of minimum discharge in July by 6% to 9% in catchments higher than 2000 m a.s.l. Towards later summer and in lower elevation catchments this effect is reduced. Considering years with below-average SWE maximum, the minimum discharge decreased to 75% of its normal level. Additionally, a reduction in SWE resulted in earlier low flow occurrence. One other important factor was the precipitation between maximum ~~snow accumulation~~SWE and summer low flow. When only ~~the years with below average precipitation amounts during~~dry preceding conditions in this period were considered, the importance of ~~snow accumulation~~maximum SWE as a predictor of low flows increased. ~~The slope of the regression between SWE_{max} and summer low flow and the elasticity index both~~We assessed the sensitivity of individual catchments to the change of maximum SWE using the non-parametric Theil-Sen approach as well as an elasticity index. Both sensitivity indicators increased with increasing mean catchment elevation~~. This indicated~~ indicating a higher sensitivity of summer low flow to snow accumulation in alpine catchments compared to lower elevation pre-alpine catchments.

1 Introduction

The shift from snowfall to rain is one of the most important effects of predicted climate change on the hydrological cycle (Feng and Hu, 2007; Laghari et al., 2012; Berghuijs et al., 2014; Zhang et al., 2015). This shift results in a decrease of the fraction of solid precipitation (snow/total precipitation, known as S/P) and thus ~~the~~in a decrease of snow accumulation especially in mid-elevation mountain ranges (Knowles et al., 2006; Pellicciotti et al., 2010; Speich et al., 2015). The decrease of S/P will affect groundwater recharge during spring and ~~might influence~~as a consequence also low streamflow values in the subsequent summer period (Bavay et al., 2009; ~~Berghuijs~~Godsey et al., 2014).

For the western US the decrease of S/P in low and middle elevations during the last decades could be explained mainly by an increase of air temperature during wet days in winter (cold season) (Knowles et al., ~~–~~2006). The ~~simultaneously found~~simultaneous change in winter precipitation amount for that region explained only a minor part of the decrease in S/P (Feng and Hu, 2007). ~~For this region the~~The largest decrease in S/P was found in March ~~leading~~for the whole study region and additionally in January near the West Coast with generally higher air temperature during winter (Knowles et al., 2006). This lead to the conclusion that an air temperature increase from December to March ~~has~~had the largest impact on snow accumulation, while warming from April to June rather ~~affects~~affected snowmelt onset, dynamics and melt-out (point in time at which all snow melt out of the catchment) (Knowles et al., 2006; Feng and Hu, 2007).

Serquet et al. (2011) used the ratio of snowfall days and precipitation days (SD/PD) to assess the effect of air temperature increase on snowfall in Switzerland. They found decreased SD/PD over the last three decades especially in lower elevations~~.~~, i.e. at regions with air temperatures close to the melting point. The decrease in SD/PD was stronger in spring than in winter (Serquet et al., 2011).

Berghuijs et al. (2014) showed that ~~the~~a higher fraction of precipitation fallen as snow is associated with higher long-term mean streamflow in comparison ~~with~~to catchments with lower snowfall fraction. Higher air temperatures during spring affect the onset of snowmelt in streamflow shifting it towards earlier spring (Barnett et al., 2005; Dankers and Christensen, 2005; Lundquist and Flint, 2006; Hanel et al., 2012; Godsey et al., 2014; Langhammer et al., 2015). These changes lead to a higher fraction of annual flow occurring earlier in the water year as evident from many studies across the western US (Cayan et al., 2001; Stewart et al., 2005; Day, 2009). However, snowmelt and consequent spring streamflow are affected by a wide range of factors, such as topography, vegetation and connected radiation as well as shading effects which might overlay the effect of increasing air temperature (Jost et al., 2007; Jenicek et al., 2012; Pomeroy et al., 2012; Kucerova and Jenicek, 2014). Earlier onset of snowmelt could, for instance, be slowed down by less shortwave radiation due to lower sun inclination in early spring (Lundquist and Flint, 2006).

While an increase of mean monthly runoff and low flows during winter and spring months were documented in several catchments in Switzerland and in other central European countries (Birsan et al., 2005; Fiala et al., 2010; Kliment et al., 2011), a significant decreasing trend of mean monthly discharge during winter was detected at selected mountain catchments in Slovakia (Blahusiakova and Matouskova, 2015).

Speich et al. (2015) demonstrated the sensitivity of catchments in the Swiss Alps to ~~the~~a reduction of snow contribution to total runoff by applying bivariate-mapping techniques. ~~The~~The combination of total runoff and snowmelt appeared to be more sensitive to predicted future changes of air temperature and precipitation than the combination of precipitation and potential evapotranspiration (Speich et al. 2015). Additionally, the elevation ~~bands above~~band between 1000 and 2500 m a.s.l. ~~and below 2500 were~~was found to be relatively more sensitive to future temperature and precipitation scenarios than lower elevation ~~catchments.~~bands. Further, Zappa and Kan (2007) demonstrated that the presence of above-average snow resources contributed to mitigating the effects of the 2003 summer drought in some high-elevation areas within the Swiss Alps.

Snow conditions in winter can effect low flows during the subsequent summer especially in areas with large differences in winter and summer precipitation. The total amount of snow precipitation in winter affects groundwater recharge and hence also runoff during dry summer periods (Earman et al., 2006; Beaulieu et al., 2012; Van Loon et al., 2015). While meteorological drivers and overall catchment storage both affect the drought duration during summer, seasonal storage in snow and glaciers affect the drought deficit (Van Loon and Laaha, 2015). However, ~~the~~ snow cannot solely explain the sensitivity to drought, although higher elevation catchments ~~are generally~~in the Swiss Alps were found to be less sensitive to drought origin~~, as~~ (Staudinger et al., 2015). Additionally, some modelling experiments ~~have~~

~~shown~~suggested larger groundwater storages in higher elevation Swiss catchments which may additionally explain the lower sensitivity of higher elevation catchments to low flows (Staudinger and Seibert, 2014~~; Staudinger et al., 2015~~).

Based on historical records from selected Sierra Nevada catchments in the western USA, every 10% decrease in snow water equivalent maximum in spring leads to a decrease of 9-22% in minimum runoff during summer months and the runoff minimum occurs about 3-7 days earlier (Godsey et al., 2014). Higher elevation catchments showed a longer memory ~~effect~~to previous seasons climate variability than lower elevation catchments (Cayan et al., 1993) and ~~an effect of~~some catchments in the Sierra Nevada mountains were affected by the snowpack of the preceding year ~~on~~during the subsequent summer runoff ~~was found for some catchments in the Sierra Nevada mountains~~ (Godsey et al., 2014).

The above mentioned ~~results~~studies show that the influence of snow amount on early spring discharge is widely studied and known. However, we still lack a quantitative assessment of the sensitivity of summer low flows on snow conditions from the preceding winter. In this study ~~the aim was~~we want 1) to quantify ~~the length of the memory effect of individual catchments in terms of the influence of winter snow conditions on summer low flows~~how long snowmelt affects runoff after melt-out and 2) to estimate the sensitivity of the catchments to changes in snowpack. We benefit from a recently generated SWE dataset which allowed for an in-depth analysis of snowpack changes and detection of melt-out dates. Our study adds to earlier studies, by focusing on the combined effect of snow and ~~summer~~liquid precipitation during the warm period and ~~their~~its varying ~~spatial and temporal influence. To explore~~importance for individual catchments. Exploring this combined effect is particularly important ~~especially~~ in humid regions ~~as~~where annual precipitation is approximately equally distributed over the year, while most studies were performed in climates with more seasonal precipitation and/or smaller precipitation amounts overall~~. Moreover~~ (such as in the western USA). Furthermore, we ~~describe different sensitivity~~set the sensitivities of low flows to varying snow conditions in ~~catchments with different~~context to simple catchment properties which offers a way to indicate regions that might become more vulnerable to droughts in the future.

2 Material and methods

2.1 Study area

We selected 14 alpine and pre-alpine catchments in Switzerland with a catchment area ranging from 0.93 to 1577 km² (Fig. 1 and Table 1). Catchments as close as possible to natural conditions were selected~~ to minimize the effect of~~, i.e. streamflow is near-natural and no major human ~~activity on runoff.~~influences such as dams or water transfer are present. Further, in the studied catchments there is ~~mostly ~~zero or only a very small area covered by glaciers (0-2%, ~~with the exception of~~except up to 4% for Vorderrhein and Simme).

2.2 Data

Daily gridded precipitation and air temperature data (2 by 2 km² resolution~~), which~~) were obtained from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss; Frei and Schär, 1998; Frei, 2014~~), were~~) and averaged over the catchment area for use in the analyses. Daily snow water equivalent (SWE) data were also available as a gridded dataset with a 1 by 1 km² resolution. The SWE was calculated based on daily snow depth observations and a snow density model (Jonas et al., 2009) using interpolation and post-processing procedures first presented in Jörg-Hess et al. (2014). In a first step, available station data were mapped to a grid using de-trended distance weighting procedures that were specifically adapted to interpolate SWE data. To further account for changes in the number of available snow stations, the gridded dataset was homogenized using the quantile mapping method. Quantile mapping is a statistical calibration method that allows a set of maps to be improved based on fewer stations, by accounting for persistent spatial patterns in maps that are based on a larger number of stations. This procedure resulted in a homogenized dataset that covers the period 1971-2012~~, and the months November to May respectively.~~. This same data set has already been adopted to update initial conditions of a hydrological model used for ensemble monthly predictions of SWE and runoff (Jörg-Hess et al., 2015). Further details on the methodology used to process the SWE data are available in Jörg-Hess et al. (2014), which further assessed the accuracy of the homogenized maps. Additionally, ~~authors showed the first usage of~~Jörg-Hess et al. (2014) used this SWE data to assess the influence of snow conditions on summer low flows for a large Swiss catchment with possible use for minimum spring and summer runoff forecast based on SWE as the only predictor.

Daily discharge data were obtained from the Swiss Federal Office for the Environment (BAFU). Data from 1971 to 2012 were used in all analyses ~~with the exception of~~except a few shorter time series, as specified in Table 1.

2.3 Statistical analysis and assessment

We selected different predictors related to winter and spring meteorological conditions and water storage conditions in the catchments (Table 2).

These predictors were tested to explain the variability of three variables describing low flow conditions: i) minimum 7-day moving average of daily discharge was calculated based on BAFU data. Different sizes of the moving window (3, 7 and 15 days) were tested without significant influence on the results. ii) The day of year of 7-day minimum of discharge was calculated from June to September to exclude low flows before snowmelt or after the onset of new winter snow accumulation. iii) Number of days below a specified discharge threshold (25% quantile of discharge from May to October).

We used ~~eight~~nine variables as predictors of future summer low flows (Table 2). ~~The~~ The advantage of this choice of predictors is that only SWE, precipitation, air temperature and runoff data are needed for their calculation. These data are available for many regions which allows to test our methods also elsewhere with possible transfer to ungauged catchments.

Late winter conditions were represented by the maximum SWE before snowmelt onset ~~was~~ calculated using the ~~above described~~ SWE data from February to May ~~in order to represent late winter snow conditions~~. We used both the maximum SWE calculated as a catchment mean and the maximum SWE calculated from the highest 50% of the catchment area, assuming that snowpack at higher elevations melts later and could be more important for summer discharges. The melt-out date was calculated from SWE data for each catchment and year. The melt-out date was defined as the first occurrence of snow free conditions (snow cover fraction less than 10%) after the day of maximum SWE. The sum of positive SWE changes (sum of new snow) and the sum of positive air temperatures were used as well. Both variables were calculated as a sum from November 1 to April 30.

While the variables related to snow describe the state of the individual catchment before snowmelt, total winter precipitation calculated from November 1 to April 30 describes the available water amount from winter precipitation. Additionally, we calculated the fraction of snowfall to total winter precipitation (S/P). Since information on whether precipitation occurred as rain or snow was not available, we used a threshold air temperature (1.1°C) to determine the phase of precipitation. The threshold temperature near 1°C was used by several authors (Dai, 2008; Feiccabrino and Lundberg, 2008) who used data from stations where the information about phase of precipitation were available. Additionally, we tested different threshold temperatures, and found no sensitivity of our results on an exact value.

The day of year with maximum SWE was used to show the dependence of low flows on this variable. ~~Using~~In this way, we could investigate if low flows occur later in the year and if ~~they~~low flows are higher with later occurrence of maximum SWE.

A current precipitation index C_{PI} (Smakhtin and Masse, 2000) was used to describe the influence of preceding liquid precipitation on low flows. C_{PI} was calculated for each month from June to September for the day when 7-day minimum discharge occurred (Eq. 1).

$$C_{PI(t)} = C_{PI(t-1)} K + P_t \,, \qquad (1)$$

where $C_{PI(t)}$ [mm] is C_{PI} for day t , P [mm] is the catchment precipitation for day t and K [-] is the daily recession coefficient, which usually varies from 0.85 to 0.98 (Smakhtin and Masse, 2000). We used a K value of 0.93 in this study. The statistical model used in our study is not sensitive to the exact value of K.

All parameters ~~except C_{PI}~~ were calculated assuming a complete data series and additionally considering only years with below-average spring and summer precipitation. ~~The aim was to separate~~By doing this the effect of spring and summer liquid precipitation on low flows could be separated and thus ~~highlight~~ the effect of snow could be highlighted.

To assess the relations between predictors and response variables we used the Spearman rank correlation coefficient and the bivariate linear regression. Most of the predictors and response variables were expressed as a percentage difference from the mean value, which enabled a comparison between individual catchments. The linear regression was computed from log-transformed variables. Prediction intervals of linear regression were used, which allowed the future observation of the response variable to be estimated. The R software was used for all calculations in this study (http://www.r-project.org/).

The slope of regression calculated using the nonparametric Theil-Sen method was used to evaluate our statistical models. The Theil-Sen slope is a median of slopes calculated for each pair of observations (Birsan et al., 2005; Pellicciotti et al., 2010). The higher the value, the steeper the slope of regression and thus the ~~relation between independent (e.g. maximum SWE) and~~more sensitive is the dependent variable (e.g. minimum discharge) ~~is more obvious.~~to the change of the independent variable (e.g. maximum SWE). The Theil-Sen linear regression model is suitable for non-normally distributed data with outliers.

~~The~~Similar to the slope of regression, the elasticity index (Eq. 2) was used to describe how sensitive the minimum discharge is to the change of SWE. The climate elasticity is often used to describe sensitivity of streamflow to the change of climate variables (Andréassian et al., 2015). A similar concept was used in this study to describe what percentage change of minimum discharge is caused by a defined percentage change of maximum SWE (Eq. 2).

$$Elasticity = \%\ change\ of\ minimum\ discharge\ /\ \%\ change\ of\ maximum\ SWE \qquad (2)$$

While the relationship between maximum SWE and minimum discharge is usually not linear, the elasticity index changes for different SWE conditions. The elasticity index in this study is usually lower than 1, which means that a particular percentage change in maximum SWE causes a lower percentage change of minimum discharge. The elasticity index was calculated from the 50% probability of prediction derived from the individual linear models.

The relative influence of snow and liquid precipitation during the warm season on low flows was analyzed calculating scores for both SWE and C_{PI} (Eq. 3 and Eq. 4).

$$\mathrm{SWEscore} = \sum_{i=1}^{n} (\mathrm{SWE_i} \times \mathrm{Qmin_i}/100)/\mathrm{n} \qquad (3)$$

$$C_{PI}\mathrm{score} = \sum_{i=1}^{n} (C_{PI(i)} \times \mathrm{Qmin_i}/100)/\mathrm{n} \qquad (4)$$

where SWE_i is maximum SWE in year i, $Qmin_i$ is the 7-day minimum discharge in a specific month of year i and $C_{PI(i)}$ is the current precipitation index on the day when $Qmin_i$ occurs. All input values are expressed as a percentage difference from the mean (e.g. a 100% SWE 100% represents the average maximum SWE in a catchment). The higher the score, the stronger the respective effect on low flows.

All analyses were done separately for each catchment and ~~mostly~~almost all for the period May to September to highlight the changing importance of snow contribution to low flows in different catchments and time. Analyses of the combined effect of snow and liquid precipitation were made only for the period from June to September, because liquid precipitation (expressed as C_{PI}) was not calculated for May. In May there is still snow in some catchments and including it in C_{PI} would ~~affect~~complicate the interpretation of the results.

3 Results

3.1 Correlation of selected predictors and response variables

Spearman rank correlation coefficients between predictors and response variables were calculated separately for three elevation classes (highest elevation catchments: above 2000 m a.s.l.; middle elevation catchments: 1300-2000 m a.s.l; low elevation catchments: 850-1300 m a.s.l) (Fig. 2). ~~Spearman rank correlation coefficients were calculated both for the whole observation period and for selected years with below-average spring and summer precipitation (Table~~ Using these three elevation classes showed changing correlations for catchments in different elevation and thus different influence of snow storage on runoff. Spearman rank correlation coefficients were displayed as heatmaps together with dendrograms showing clusters of similar predictors and response variables (Fig. 2).

The maximum SWE (both averaged per catchment and in upper 50% of the catchment area) was in ~~3). This was done to separate the effect of snow and reduce the effect of liquid precipitation. This way we can conclude that snow is more important for low flows in May and June and its role decreases in August and September. In contrast, the importance of liquid precipitation on low flows generally increases from June to September. However, the snow remains important even in late summer in the case that there is below-average preceding precipitation (Table 3, “low C_{PI}”).~~

~~The 7-day minimum discharge was predicted best by the sum of winter precipitation from November 1 to April 30 in the period from May to July. In August, maximum SWE predicts minimum discharge slightly better than winter precipitation (Table 3). The correlation between minimum discharge and S/P index was surprisingly weak with significant correlations (0.05 level) only in June and July. The day of year of 7-day minimum discharge could be correlated best with winter precipitation. The correlations are rather weak, although~~ most ~~of them are significant at the 0.05 level. There is a negative trend in~~ cases the best predictor for higher elevation catchments during summer (July and later). Additionally, maximum SWE and the sum of new SWE were better predictors than winter precipitation in snow dominated catchments to predict the number of days with ~~discharge below the specified threshold in case of~~ low discharge (No. days < Q25%). On the contrary, winter precipitation was a better predictor than maximum SWE for lower elevation catchments (June to September) and for middle elevation catchments during spring (May, June). Furthermore, the melt-out date explained a relatively high portion of the inter-annual variability during spring time for the lower elevation catchments (~60%).

Minimum discharge and S/P were surprisingly weak but significantly correlated (0.05 level) from June to July (Fig. 2). Less prediction ability in both higher and lower elevations could be explained by a general reduced importance of snow in lower elevation catchments and high snowfall fraction (> 80%) in higher elevation catchments with a consequent smaller variability of snowfall fraction in higher than in lower elevation catchments.

The role of spring and summer liquid precipitation (expressed as C_{PI}) changed both for elevation classes and in different months showing a decreasing importance of preceding precipitation in the warm period from lower elevations to higher elevations and an increasing ~~peak SWE, sum of new SWE and winter precipitation. The number of days~~ importance from June to September (Fig. 2). The correlation between predictors and the day of year with minimum discharge changed for three elevation classes showing decreasing correlations with ~~discharge below the specified threshold decreased as well~~ SWE-related predictors and increasing correlations with ~~a later occurrence of peak SWE.~~ preceding liquid precipitation (C_{PI}) from higher to lower elevations.

Despite the significance of the correlations ~~found~~, their values are not high which indicates that low flows are influenced by more than a single variable~~.~~ (maximum explained inter-annual variability in the group was 60%). Additionally, some of the predictors are not mutually independent~~.~~ (see dendrograms in Fig. 2). Since our focus was primarily on middle and high elevation catchments as well as on summer months, maximum SWE seems to be the best predictor, although differences are not large.

3.2 Influence of maximum SWE on low flows

Snow melt affects groundwater recharge and thus it has an effect on low flow values even after the melt-out of the snowpack. ~~However, groundwater data are usually not accessible at the catchment scale and have to be simulated. Thus, we~~We used maximum SWE as ~~a~~ variable to predict 7-day minimum discharge (Fig. 3). Snow~~2). A decrease of snow~~ influence decreased with ~~time is seen in~~ monthly progression as shown for selected catchments representing ~~different~~high, middle and low elevation ranges. For the three elevation ranges maximum SWE differed not only in the overall amount but also in its annual variability (Fig. 3).

The ~~relationship~~relationships between the 7-day minimum discharge and maximum SWE (Fig. ~~2~~3) are characterized by a large variability~~ indicating~~. This indicates that only a certain portion of low flow variability can be explained using ~~the~~ maximum SWE. Coefficients of determination (R^2) were not higher than 0.65 for high elevation catchments during late spring and early summer. ~~However, R^2 does not describe either an increasing or decreasing trend in~~ In general, the ~~data. Therefore,~~ability of maximum SWE to explain minimum discharges decreased from June to September and from higher to lower elevations.

The relationship between predictor and response variable were in more detail described by the Theil-Sen slope of the regression and by the elasticity index ~~were used to describe the relationship between predictor and response variable~~ (Fig. ~~3 and~~4, Fig. ~~4~~5 and Fig. 6). Both Theil-Sen Slope and elasticity describe the sensitivity of low flows to both decrease and increase of maximum SWE~~ compared to the mean value. The sensitivity of individual catchments strongly depends on catchment properties, such as mean catchment elevation, maximum SWE and S/P (Table 4). These correlations clearly varied for different months and reached their maximum in July and August and they decreased in September~~.

The elasticity index for high (mean elevation higher than 2000 m a.s.l.), middle (mean elevation between 1300 and 2000 m a.s.l) and low (mean elevation between 850 and 1300 m a.s.l.) elevation catchments (Fig. 4) decreased progressing from June to September. The elasticity index for high elevation catchments was for each month higher than the elasticity index for middle and low elevation catchments and the elasticity index of the middle elevation catchments was higher than for the low elevation catchments. While the spread of the elasticity indices per elevation class was about equal for high and middle elevation catchments the spread for the low elevation increased progressing from month to month. This means the general sensitivity to SWE is lower for lower and middle elevation catchments than for high elevation catchments and decreases for each class progressing from June to September.

Theil-Sen slopes for each catchment and for every week from the beginning of May to the end of September, allowed an analysis of the sensitivity in terms of the memory effect of each catchment (Fig. ~~4~~5). These weekly slopes describe how long water from snow melt contributes to runoff formation and thus how long ~~snow~~snowmelt affects low flows. With this approach, a significant effect of snow on low flows became visible during the whole summer and until September for catchments higher than 2000 m a.s.l. (Fig. 5). Snow affected low flows until July in catchments with mean catchment elevation in the range of 1500 to 2000 m a.s.l. However, snow did not affect summer low flow (July to September) in catchments lower than 1500 m a.s.l. Here, snow affected low flows during May and June only, which is probably caused mostly by lower SWE (maximum less than 250 mm).

~~The effect~~There was a clearly longer snowmelt contribution to minimum discharges in higher elevation catchments even when different ~~high peak~~melt-out dates (black points in the Fig. 5) were considered. This could be related to more available water released from snow in higher elevation catchments despite their steeper slopes and shallow soils. The negative correlations in some of the lower elevation catchments (usually not statistically significant) indicates a mixed effect of snow and liquid precipitation in the warm season.

Additionally, Theil-Sen slopes for each catchment and for every week from the beginning of May to the end of September were calculated and set in context to the melt-out days only for situations with dry preceding conditions, i.e. when liquid precipitation prior to minimum discharge in a specific week was below average (results not shown in the paper). Considering only these situations, the sensitivity of minimum discharges to maximum SWE ~~is~~increased. This was due to the reduced influence of liquid precipitation in the warm season. As a consequence, snow became more important for groundwater recharge and thus any decrease/increase of snow storage in individual year resulted in a more sensitive response of minimum discharge.

The sensitivity as described by Theil-Sen slopes of individual catchments strongly depends on catchment properties, such as mean catchment elevation, maximum SWE and S/P (Table 3). The significant positive correlations (Table 3) imply that the sensitivity of minimum discharge to maximum SWE increases with increasing value of the catchment property. Summer minimum discharges in higher elevation catchments with steep slopes, high drainage density and high maximum SWE were more sensitive to maximum SWE changes than minimum discharges in lower and less steep catchments with lower drainage density and low maximum SWE (Table 3). These correlations clearly varied for different months and reached their maximum in July and August and they decreased in September. Maximum SWE affects groundwater recharge and influences mainly the volume of water in the groundwater zone. ~~The effect of elevation~~Elevation influences mainly the timing of snowmelt with later snowmelt onset in higher elevations. Thus, the water inflow into the groundwater zone occurs later in spring and it is distributed over a longer time period. ~~Therefore,~~Which is why groundwater recharge from snow affects low flows even in late summer. Maximum SWE shows significant correlations in June through September, while winter precipitation was not significantly correlated to the Theil-Sen slopes (Table 3). Additionally, Spearman rank correlations were not significant with regard to catchment area.

The elasticity calculated for the 50% probability of prediction enables us to describe the impact of future changes of snowpack either due to natural annual variability or due to ~~the~~ predicted climate change (Fig. ~~5). In case of basins~~6). For catchments higher than 2000 m a.s.l., every decrease of the maximum SWE by 10% will cause a decrease of minimum discharge in July by 6% to 9% (Fig. ~~5~~6, top right). This means that the decrease of minimum discharge is almost proportional to the decrease of SWE in some cases (Ova Da Cluozza and Ova dal Fuorn). For catchments with a mean elevation between 1500 and 2000 m a.s.l, the decrease of minimum discharge ranges from 2% (Grande Eau) to 5% (Simme). The lowest catchments are characterized with even lower values indicating that any decrease of maximum SWE will not significantly affect low flows at least from July to September. However, there is some small effect during June (Fig. ~~5~~6, top left). Generally, the sensitivity of low flows to the change of SWE increases with elevation and decreases from June to September. However, the elasticity is not linear and the decrease of low flows accelerates with decreasing SWE.

~~The volume of accumulated snow~~Maximum SWE for each catchment impacted the day of year with minimum discharge (Fig. ~~6). The~~7). Our hypothesis was that minimum summer discharge would occur later in the year for higher ~~peak~~maximum SWE. However, later low flow occurrence may be additionally influenced by a later melt-out and thus later maximum of groundwater storage. Low flows occurred in September and October for higher elevation catchments with a higher SWE maximum~~.~~ (Fig. 7, brown points). In contrast, July and August are typical months for low flow occurrences for lower elevation catchments with lower SWE maximum~~.~~ (Fig. 7, green points). On average, every decrease in ~~peak~~maximum SWE by 100 mm resulted in ~~runoff~~discharge minima occurring about 12 days earlier. However, inter-annual variability markedly increases in lower elevation catchments indicating an increasing role of summer precipitation.

3.3 Combined effect of snow conditions and preceding precipitation on summer low flows

Snow is an important component for groundwater recharge during the snowmelt period. However, the relation between snow and minimum discharge during the summer period is not often clear and may be overlaid by several other factors, mostly precipitation after melt-out. To demonstrate the combined effect of snow and precipitation on summer low flows, three snow-dominated catchments in high and middle elevations (Ova da Cluozza, Vorderrhein and Lümpenenbach) were selected as typical representatives and then further analyzed.

For low C_{PI} years~~ with lower than average preceding precipitation~~, snow became a better predictor to explain the variability of minimum discharge indicated by steeper regression slopes and higher coefficients of Spearman rank correlation (Fig. ~~7~~8, top). Minimum discharges did not decrease much with a low SWE and ~~above-average preceding precipitation~~high C_{PI} (top plots, ~~blue~~dashed lines). However, snow was more important for ~~situations with~~ low ~~liquid precipitation. In these cases,~~C_{PI} years, where minimum discharges were more sensitive to the change of summer precipitation (top plots, ~~red~~solid lines).

The minimum discharge decreased significantly in years with lower than average ~~SWE~~ maximum SWE and average preceding precipitation compared to years with higher than average SWE maximum and same amount of preceding precipitation (Fig. ~~7~~8, bottom). For the Ova da Cluozza catchment, as an example, and considering only years with above-average SWE maximum, there is a 50% probability that given an average preceding precipitation there will be a 7-day minimum discharge equal or higher than 107% of its normal in July. On the contrary, considering years with below-average SWE maximum, the 7-day minimum discharge will decrease to 75% of its normal level. Similar changes are predicted both for higher elevation catchments and lower elevation catchments, although in the latter this decrease is somewhat smaller.

The combined effect of snow and liquid precipitation on low flows was analyzed using "score plots". In these plots the position of each catchment is shown according to its average influence of snow and precipitation on the 7-day minimum discharge separately for the period from June to September (Fig. ~~8). The SWE score (x-axis) and C_{PI} score (y-axis) were calculated according to the following equations (Eq.~~9). ~~3 and Eq. 4).~~

$$\mathrm{SWEscore} = \sum_{i=1}^{n} (\mathrm{SWE_i} \times \mathrm{Qmin_i}/100)/n \qquad \cancel{(3)}$$

$$C_{PI}\mathrm{score} = \sum_{i=1}^{n} (C_{PI(i)} \times \mathrm{Qmin_i}/100)/n \qquad \cancel{(4)}$$

~~where SWE_i is peak SWE in the year i, $Qmin_i$ is the 7-day minimum discharge in the specific month of year i and $C_{PI(i)}$ is the current precipitation index on the day when $Qmin_i$ occurs. All input values are expressed as a percentage difference from the mean (e.g. SWE equal to 100%,~~

~~means the average maximum of SWE in a catchment). The higher the score, the stronger the respective effect on low flows.~~

Points located below the $y=x$ line indicate catchments where snow has a stronger effect on low flows compared to rain. Catchments with a mean elevation higher than 1600 m a.s.l in June and July and higher than 2000 m a.s.l in August are typical representatives for a stronger effect of snow~~.~~ (Fig. 9, brown points). Points located above the line indicate catchments with a stronger effect of rain on low flows (lower elevation catchments in June, July and August and all catchments in September). Progressing from June to September the relative effect on low flows shifted from the highest elevation catchments showing a stronger effect of snow and a weaker effect of liquid precipitation which is reversed by September.

4 Discussion

4.1 The role of catchment properties

~~We explored the dependencies of summer low flows on different meteorological predictors related to the winter period.~~ Based on our results it seems that dependencies between predictors and response variables may be connected to catchment properties and climate drivers to some degree, such as elevation and thus maximum SWE and S/P. However, the variability of low flows cannot be explained by one single parameter, which are indicated by relatively low values of Spearman rank correlation~~ (despite their prevailing significance at 0.01 level).~~.

The correlation of the dependencies of summer low flows on catchment elevation can be explained by lower air temperature in higher elevation and thus more snow accumulation and may be supported by results of Birsan et al. (2005) and Staudinger et al. (2015) in Swiss catchments. Staudinger et al. (2015) showed that higher elevation and steeper catchments were less sensitive to droughts mainly because of an increasing snow influence but also because of potentially larger storages for the higher elevation catchments of the selection. Our results showed that this sensitivity might increase with decreasing SWE either due to natural annual variability or due to climate change.

The elevation was also related to the memory effect of individual catchments which was generally longer for the highest elevation catchments than for middle or low elevation catchments. However, even with the highest elevation catchments, we did not find any significant correlations of snow and minimum discharges in October and later. In contrast, Godsey et al. (2014) found significant correlations even with the previous year's snowpack for some catchments in the western ~~US. Summer precipitation in Switzerland is relatively higher than summer precipitation in the western US and, as shown in our study, summer precipitation dominates over the effect of snow, especially with an increasing time from the snowmelt period, which explains the contrary results for the western US and Switzerland. We also found negative correlations between maximum SWE and low flows in few cases in low elevation catchments. However, these negative correlations cannot be explained by any physical process and they should be considered as a noise~~USA.

A longer memory effect in catchments with higher elevation is not only connected to higher snowpack accumulations but also to the simple fact that snowmelt occurs later in spring and persists longer compared to catchments in lower elevations (often until late spring or even early summer). The dependence of the day of year of peak SWE on day of year of minimum discharge was confirmed in our study. Similar dependences were found also in Whitaker et al. (2008), using the timing of the first significant snowmelt event instead of the day of year of peak SWE. A negative trend in the number of days with discharge below specified threshold in case of increasing peak SWE was proved. A 25% quantile of discharge from May to October was used in this study. A 10% quantile was also tested and found to have only minor impact on the results.

As documented by Beaulieu et al. (2012) in British Columbia, snow from headwater parts of catchments contributes significantly to base flow in lower parts of the catchments during summer. Earlier snowmelt onset and thus decrease of minimum streamflow has been observed (Jefferson, 2011) and a further shift of snowmelt towards earlier spring is predicted (Cayan et al., 2001; Barnett et al., 2005; Stewart et al., 2005; Bavay et al., 2009; Godsey et al., 2014).

~~4.2 Consequences of climate change~~

Of course there are many other factors together with snow in winter that influence and can explain low flow conditions in summer. For instance, evapotranspiration may change from year to year. In this study we did not do a thorough analysis of potential and actual evapotranspiration because of a lack of available data. However, water balance component estimates for the entire Switzerland during the last 100 years show that annual precipitation and runoff vary far more than evaporation (Hubacher and Schädler, 2010). Given that, we expect that variations of ET from year to year are relatively minor compared to changes in SWE and if there are any, than we would expect more actual evapotranspiration in wet years and less in dry ones. This feedback leads to the hypothesis that actual evapotranspiration is less useful as predictor for low flows. We tested also drainage density to account for landscape draining properties (e.g. Tague and Grant, 2004) and found significant correlation of low flow sensitivity to the change of maximum SWE (Table 3). Draining properties together with catchment storage properties may help understanding the process causality leading to summer low flow. Combining this kind of catchment properties with the snow information might be useful for prediction. However, in this study we explored and quantified the general dependency and sensitivity to winter snowpack in humid regions.

However, the results presented in this study do not explain the process causality in detail. It means we quantified the relations based on data we used, but process-based understanding at the catchment scale is limited and has to be further investigated.

4.2 Influence of changing snow conditions

The influence of snow conditions on summer low flow will likely decrease due to predicted air temperature increase during winter and thus the decrease of S/P ratio and SWE in middle elevations. The snow fraction has an important effect on not only annual discharge (Berghuijs et al., 2014; Speich et al., 2015; Zhang et al., 2015) but also on summer low flows as documented by Godsey et al. (2014) in the western US and Laghari et al. (2012) in Austria. Our results are similar for high and mid elevation catchments in Switzerland, and based on these studies, we may conclude that summer low flows are significantly sensitive to any SWE changes. Although~~,~~ our study did not focus on existing trends in data, we expect a reducing effect of snow on late summer low flows in the highest elevation catchments. This reduction might increase problems with water availability in affected regions.

We did not explore possible impact of climate change on SWE and minimum discharges, such as relations between possible warming in the cold season and minimum discharges in the warm season or explore if any SWE decrease will occur related to it. However if there was a SWE decrease, then the same percentage decrease of SWE in higher elevation catchments will result in a stronger percentage decrease of minimum discharges than the same percentage decrease of SWE in lower elevation catchments (see Fig. 6 showing the elasticity).

In this study we looked at catchment mean elevations and for some analyses we also classified catchments as high, mid or low elevation catchments. In practice this might be oversimplified as there is generally a large gradient of precipitation and S/P ratios across elevation. Hence, also depending on the percentage of a catchment that is well below 0°C for most of the winter even with warming conditions the effect of SWE changes will be more or less strong. Nevertheless, we argue that the quantification method introduced in this study could be applied also for a more discretized set up with regard to relevant elevation zones.

4.3 Combined effect of snow and precipitation

The correlation between minimum discharge and maximum SWE~~,~~ considering years with little rain~~,~~ was higher than in years with a lot of rain. Low flows are usually higher during years with above-average snow conditions. Even in the case of low antecedent precipitation, low flow was higher than in years with below-average snow conditions. Therefore, snow plays an important role, although below-average snow conditions do not necessarily indicate below-average low flows. Preceding precipitation seems to be more important in this case. Because of the combined effect of snow and summer precipitation on summer low flows, snow-related parameters cannot fully explain the annual variability of low flows in humid regions as documented by Godsey et al. (2014) for strongly seasonal regions even for the highest elevation catchments. Nevertheless, most of detected trends in our study ~~(using Theil-Sen slope)~~ were significant at less than the 0.05 level, showing the significant influence of snow on summer low flows.

The decrease of maximum SWE and snowfall fraction increased the relative importance of rain during summer and rain thus became a relatively more important source for groundwater recharge. ~~A~~Our results showed that the continuous decrease of maximum SWE and snowfall fraction in the future might increase the sensitivity of catchments in mid and high elevations to hydrological droughts. This conclusion is in accordance with results of Birsan et al. (2005).

We chose the period from May to September to show the changing importance of snow contribution to low flows in different catchments, both in lower and higher elevations. We also tested the effect of maximum SWE on summer minimum discharge (June-August, not shown in this paper). The results for most of catchments are very similar to existing relations calculated for August because most of summer minimum discharges occur in August. Clearly we see the lowest summer flow as a compelling response variable, given the water management interest and possible issues connected to it. However, for the development of the role of snow compared to liquid precipitation this one response variable is not sufficient.

Our results do not provide a general answer to the question whether snow storage is more important than precipitation. Due to moderate humid climate in Switzerland with precipitation almost equally distributed in a year (opposite to western US), the aim was to show the combined effect of snow and liquid precipitation and their changing role in time (in different months) and in catchments with different elevation. Summer precipitation in Switzerland is relatively higher than summer precipitation in the western USA and, as shown in our study, summer precipitation dominates over the effect of snow, especially with an increasing time from the snowmelt period and with decreasing elevation. This combined effect explains the contrary results for the western USA and Switzerland.

4.4 Practical use of a quantification of snow influence on summer low flows

We used winter precipitation as a predictor and we expected similar results as using maximum SWE as predictor. Winter precipitation (from November to April) is highly correlated with SWE and we expect increasing mutual correlation for higher elevation catchments with higher S/P. Despite higher correlations in some cases (Fig. 2), we consider winter precipitation to be less suitable as a predictor than maximum SWE. Maximum SWE showed significant correlations with the Theil-Sen slopes in June through September, while winter precipitation was not significantly correlated to any of these sensitivity parameters (Table 3). Additionally, winter precipitation is not corrected for undercatch of snowfall. Thus, we expect larger errors varying between stations according to site conditions and wind speed. Given these facts and given that maximum SWE showed better prediction ability compared to winter precipitation for higher elevation catchments maximum SWE seems to be suitable predictor for forecast models. Hence, we believe that SWE data offers a chance to improve hydrological prediction models.

Our results quantified the effect of snow on minimum discharges when liquid precipitation is below average (or opposite, when SWE is below average) as documented in Fig. 8. This could increase the reliability of predictions of minimum discharge during summer. Additionally, we provided information about sensitivity of low flow in individual catchments to changes in maximum SWE using prediction intervals showing the 50% probability as well as prediction bands enabling the prediction of future observation. With this approach, it was possible to quantify not only the effect of snow storage on minimum discharge, but also on other low flow parameters, such as length of the period with minimum discharge, day of year of minimum discharge occurrence and number of days below a specified runoff threshold.

We used new SWE data covering the entire Switzerland. From our study we see a big potential to use this data for instance to regionalize the catchment sensitivity and the length of snowmelt contribution to runoff in poorly gauged areas.

5 Conclusions

~~This~~In this study we described and quantified the influence of winter and spring snow conditions on summer low flows. Specifically, we investigated the memory effect related to snow influence in runoff and the sensitivity of the catchments to low flow reduction due to any change of snowpack. The main conclusions are the following:

- ~~Snow~~Snowmelt significantly affected ~~low flows~~minimum discharge in May to September (with decreasing importance) for catchments higher than 2000 m a.s.l., up to, in July and August in mid-elevation catchments and only in June and July in the lowest elevation catchments.
- The sensitivity of low flows to maximum annual SWE was higher for catchments at higher elevation.
- Low flows occurred later in the year for years with above average snow accumulations. ~~A~~Considering the mean day of minimum discharge occurrence in all study catchments, a decrease of maximum snow accumulations by 100 mm resulted in earlier runoff minima by 12 days.
- Maximum SWE showed the best prediction ability from all winter-related predictors used in this study especially for higher elevation catchments. Applicable results were achieved also with winter precipitation (November-April). However, winter precipitation is not suitable to describe the catchment sensitivity and they are not corrected for undercatch. Thus, using maximum SWE is recommendable for sensitivity studies.
- Snow and summer precipitation had a combined effect on summer low flows, and snow accumulation alone cannot ~~alone~~ explain the annual variability of low flows even in high-elevation catchments. Snow was a better predictor for the variability of low flows when only years with lower than average preceding precipitation were considered.

However, even if both snow and liquid precipitation are considered, there is still some portion of annual variability which cannot be explained by these two predictors.

– ~~Smaller values for SWE and snowfall fraction were related to an increased relative importance of rain during summer for low flows.~~Summer low flows are significantly sensitive to any SWE changes. Thus, a reducing effect of snow on late summer low flows in highest elevation catchments is expected due to predicted climate changes. As a consequence the sensitivity of catchments in mid and high elevations to meteorological droughts might increase.

Author contribution

M. Zappa and J. Seibert initiated the project. M. Jenicek developed the methodology (with contributions of Jan Seibert) and performed all analyses. M. Zappa, M. Staudinger and T. Jonas prepared input meteorological data used for analyses. M. Jenicek prepared the manuscript with substantial contributions from all co-authors.

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Tables

Table 1. Study catchments and selected characteristics (S/P refers to the ratio of snowfall to total precipitation).

Catchment (gauging station)	Area (km²)	Mean elevation (m a.s.l.)	Elevation range (m a.s.l.)	Mean slope (°)	Drainage density (km.km^{-2})	Mean SWE$_{max}$ (mm)	Mean melt-out	S/P [-]	Winter precipitation (mm)	Data ~~period~~from (to 2012)
Dischmabach (Davos)	42.9	2368	1667-3138	22.9	4.44	484	26 Jun	0.97	365	1971–~~2012~~
Ova Da Cluozza (Zernez)	27.0	2361	1507-3160	26.8	3.75	339	22 Jun	0.98	349	1971–~~2012~~
Ova Dal Fuorn (Zernez)	55.3	2328	1706-3156	18.9	3.59	339	15 Jun	0.97	338	1971–~~2012~~
Hinterrhein (Fürstenau)	1577	2113	649-3406	21.9	3.64	333	1 Jul	0.91	403	1974–~~2012~~
Vorderrhein (Ilanz)	774	2023	691-3605	23.0	3.69	391	27 Jul	0.88	627	1971–~~2012~~
Riale di Calneggia (Cavergno)	23.9	1986	883-2911	29.1	3.87	423	15 Jun	0.88	790	1971–~~2012~~
Allenbach (Adelboden)	28.8	1851	1296-2753	19.7	3.94	351	17 Jun	0.78	720	1971–~~2012~~
Simme (Oberwil)	344	1632	776-3242	18.1	3.54	530	16 Jul	0.74	729	1971–~~2012~~
Grande Eau (Aigle)	132	1557	417-3204	21.1	3.50	249	28 Jun	0.71	789	1971–~~2012~~
Lümpenenbach	0.93	1318	1100-1515	15.1	~~3233~~3.11	207	10 May	0.59	883	1974–~~2012~~
Emme (Eggiwil)	124	1275	581-2220	14.2	3.44	185	17 May	0.59	680	1975–~~2012~~
Sitter (Appenzell)	74.4	1247	769-2501	17.8	3.56	193	25 May	0.62	787	1971–~~2012~~
Sense (Thörishaus)	351	1068	551-2181	9.9	~~95~~3.14	94	8 May	0.39	588	1971–~~2012~~
Gürbe (Belp)	116	845	518-2169	8.7	3.52	51	28 Apr	0.41	551	1971–~~2012~~

Table 2. Predictor and response variables used in analyses.

Predictor variables	Response variables
Maximum of SWE during winter before melting (catchment mean)	Minimum of 7-day moving average of discharge
Maximum of SWE during winter before melting (SWE mean calculated from higher situated 50% of catchment area)	Day of year (DOY) with 7-day minimum of discharge
~~Sum of winter precipitation (November-April)~~Melt-out date (Snow-free date)	Number of days below specified runoff threshold (25% quantile of runoff from May to October used)
Sum of winter precipitation (November-April)	
Rate of snowfall vs. total winter precipitation (S/P)	
Sum of positive SWE changes from November to April	
Sum of positive air temperatures from November to April	
Current precipitation index C_{PI} (Smakhtin and Masse, 2000)	
Day of year (DOY) with maximum SWE	

Table 3. Spearman rank correlation coefficients for the relation between catchment properties and Theil-Sen slopes (TS), which were computed for assessing the low flow sensitivity to peak SWE. Statistically significant correlations (at the 0.05 level) are shown in bold.

Catchment property	TS May	TS Jun	TS Jul	TS Aug	TS Sep
Area	0.18	0.02	-0.12	-0.17	0.16
Elevation	-0.09	**0.58**	**0.88**	**0.80**	0.52
Slope	0.07	0.28	**0.83**	**0.73**	0.49
Drainage density	-0.42	0.52	**0.60**	**0.74**	0.42
Maximum SWE	0.00	**0.67**	**0.60**	**0.57**	**0.66**
S/P	-0.13	**0.62**	**0.87**	**0.84**	**0.54**
Winter precipitation	0.41	-0.29	-0.32	-0.39	-0.17

Figures

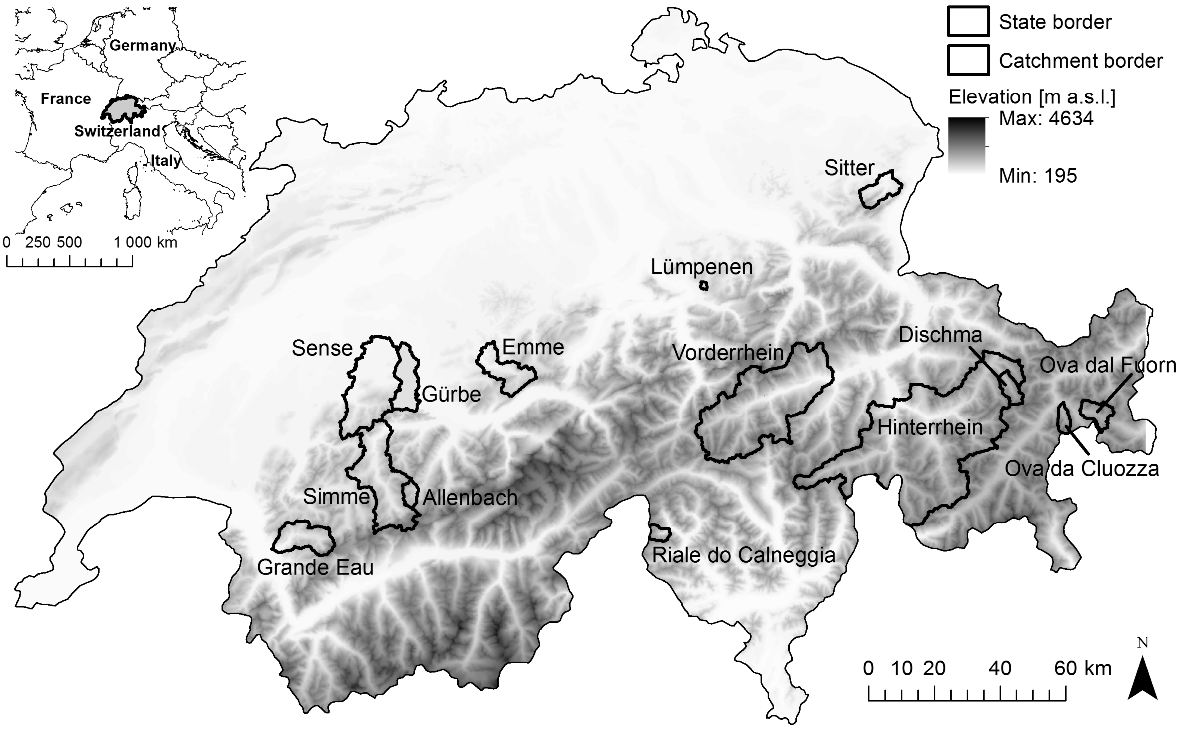

Figure 1. Location of the study catchments within Switzerland.

~~Figure 2.~~

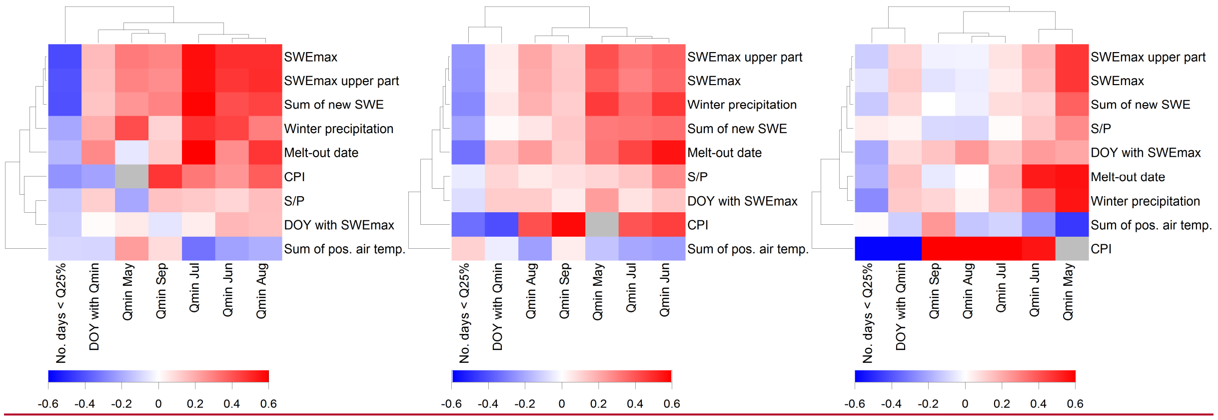

Figure 2. Heatmaps showing Spearman rank correlation coefficients for all predictors (rows) and response variables (columns) separately for three elevation groups. Left: catchments with mean elevation higher than 2000 m a.s.l.; Middle: catchments with mean elevation between 1300 and 2000 m a.s.l.; Right: catchments with mean elevation between 850 and 1300 m a.s.l. Euclidean distance used for clustering. Gray color used for NA values.

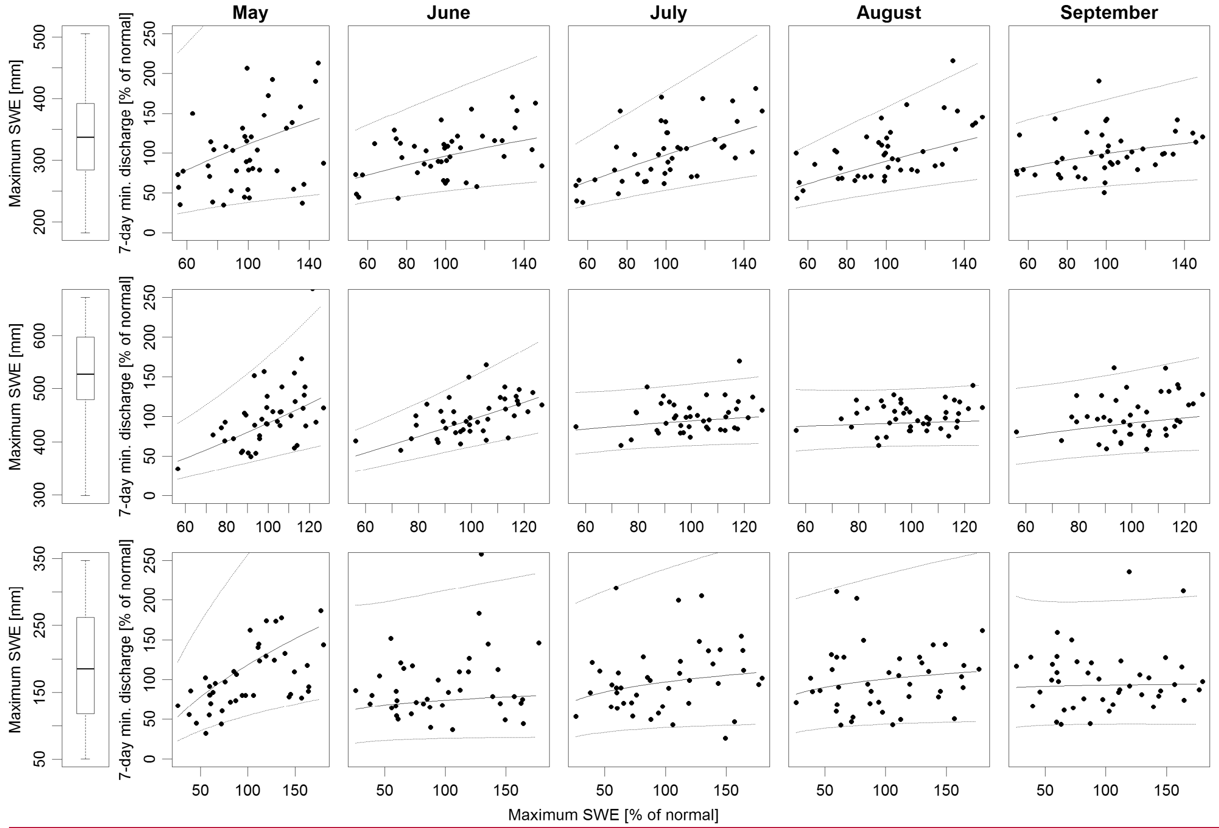

Figure 3. Dependence of 7-day minimum discharge on maximum SWE for individual months. Top: Ova da Cluozza River representing a high elevation catchment with a mean catchment elevation of 2361 m a.s.l., correlations from May to September are statistically significant (0.05 level). Middle: Simme River, representing a middle elevation catchment with a mean catchment elevation of 1632 m a.s.l., correlations from May to June are significant. Bottom: Sitter River as a representative of a low elevation catchment with a mean catchment elevation of 1247 m a.s.l., only the correlation in May is significant. Solid lines represent the low flow occurring with a 50% probability, dotted lines represent the 95% prediction interval.

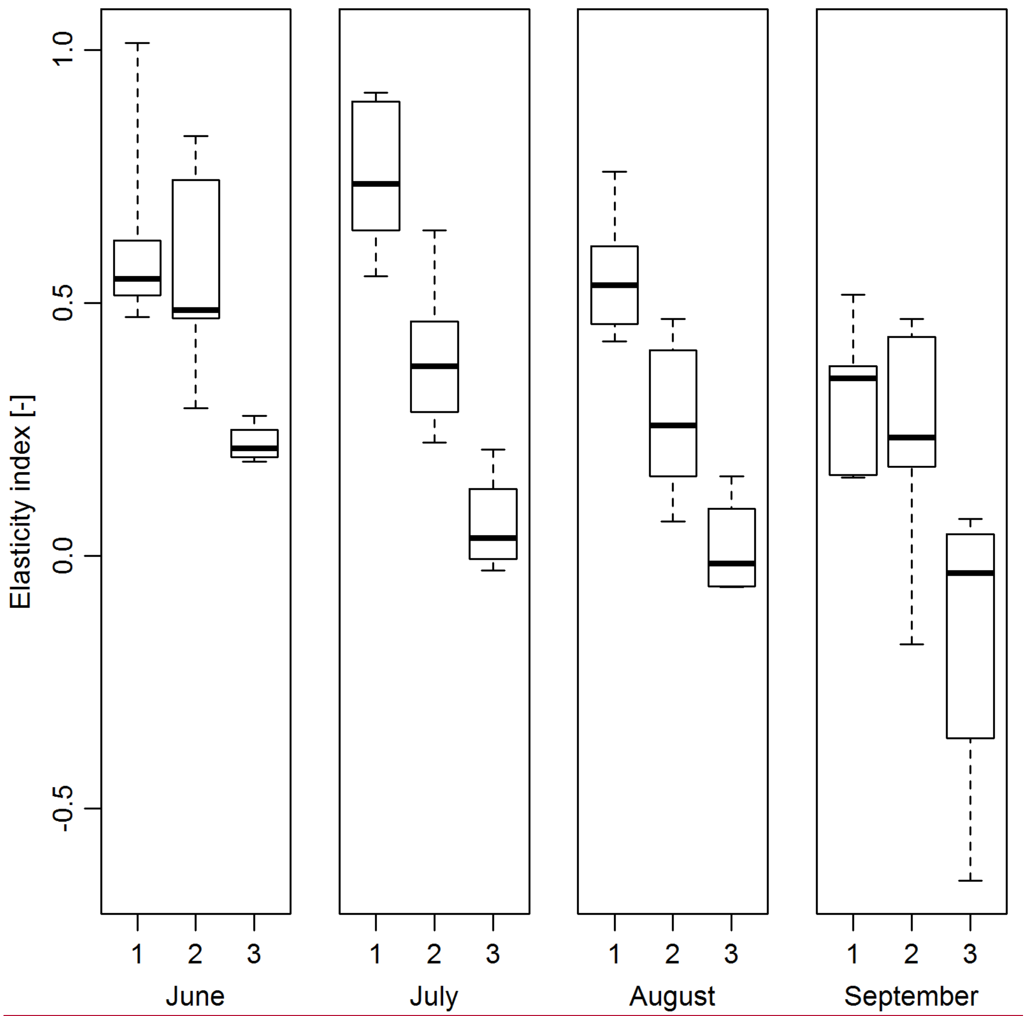

Figure ~~3~~4. Elasticity index for all catchments classified according to elevation describing the sensitivity of 7-day minimum discharge on maximum SWE for individual months. Elevation classes on x-axis: 1 – catchments with mean elevation higher than 2000 m a.s.l.; 2 – catchments with mean elevation between ~~1400~~1300 and 2000 m a.s.l.; 3 - catchments with mean elevation between 850 and ~~1400~~1300 m a.s.l. The boxes represent the 25%, 50% and 75% quantiles and the whiskers represent minimum and maximum values.

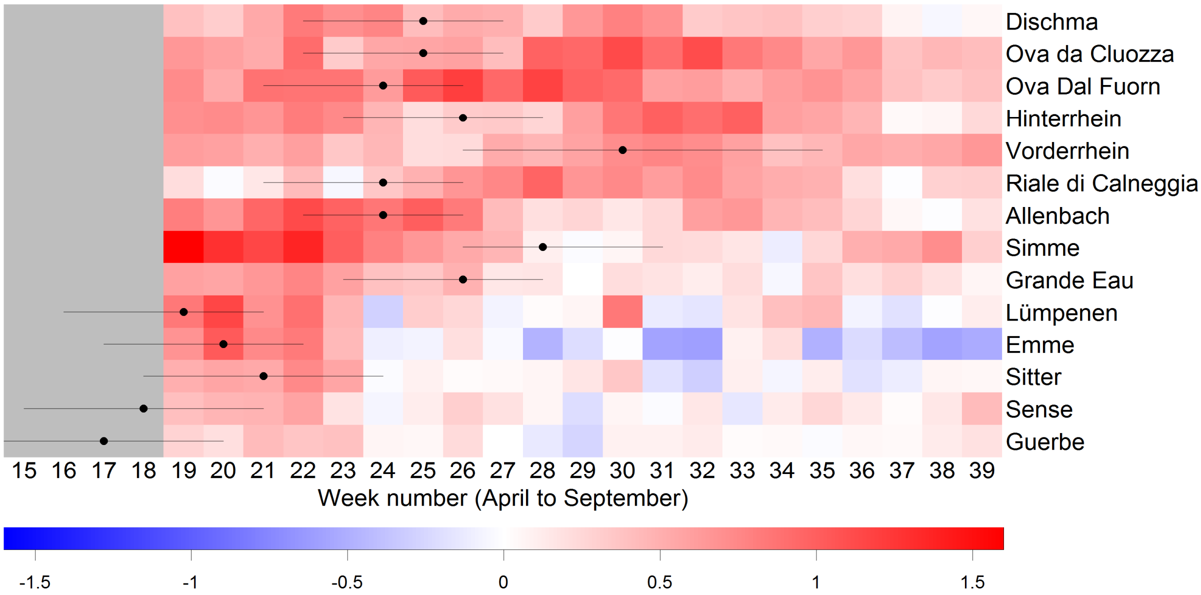

Figure ~~4~~5. Dependence of 7-day minimum discharge on maximum SWE for all studied catchments (sorted by elevation from highest to lowest) for individual weeks from the beginning of May (week 19) to the end of September (week 39). ~~Numbers provide the~~April (weeks 15-18) was not included in calculation. Color key provides Theil-Sen slopes values ~~between the variables. Significant correlations (0.05) are given in bold~~. Red indicates positive effect of SWE on minimum discharge (positive slopes), blue indicates negative effect of SWE on minimum discharge (negative slopes). Black points indicate average week of melt-out, whiskers represent 10% and 90% quantiles.

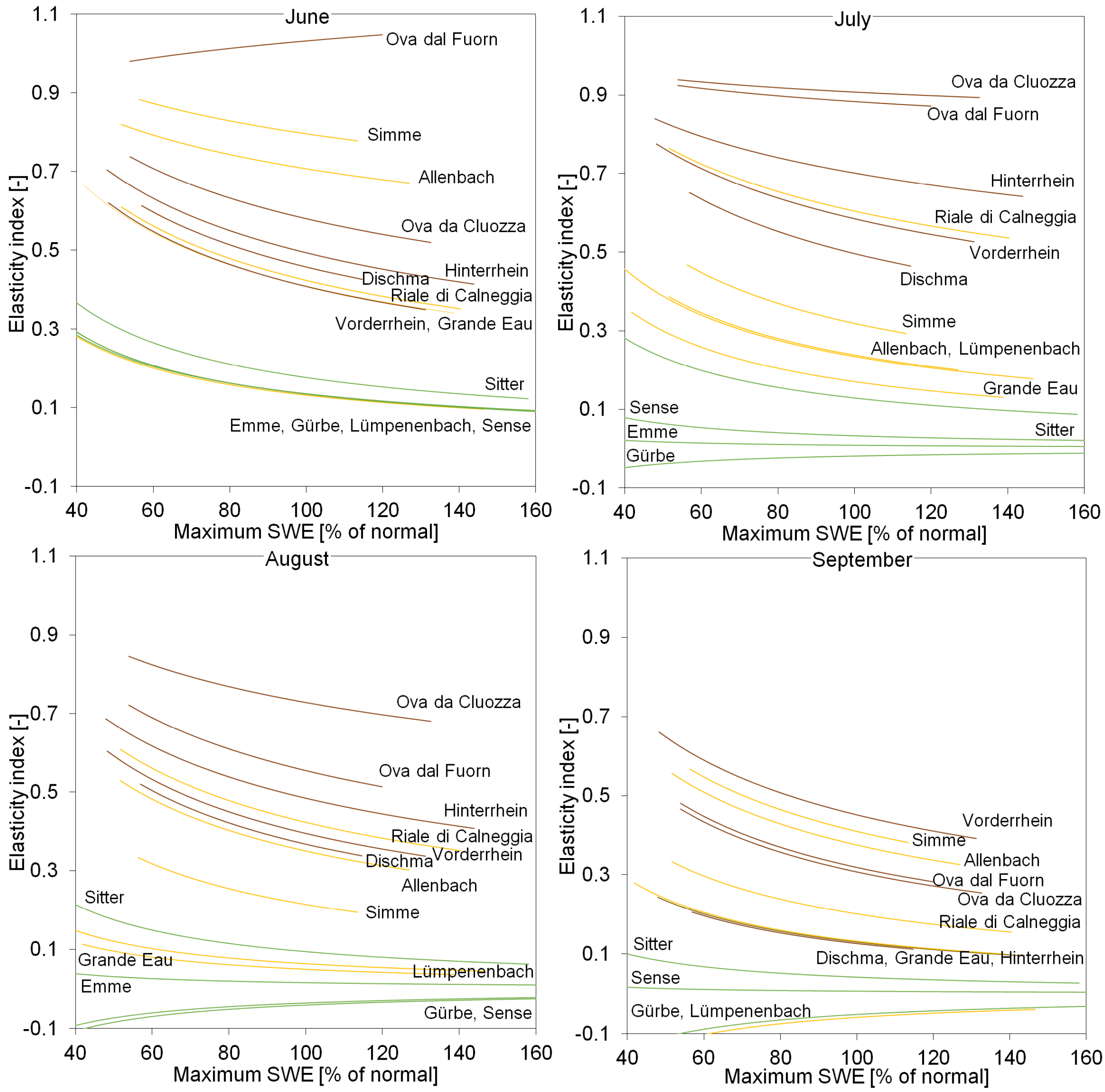

Figure ~~5~~6. Elasticity index showing the sensitivity of minimum discharge to changes in SWE. The index was calculated from the 50% probability of prediction. Line colors indicate the catchment group according to mean ~~elevations~~elevation (dark brown: ~~highest; dark~~>2000 m a.s.l.; light brown: 1300-2000 m a.s.l.; green: ~~lowest).~~<1300 m a.s.l.).

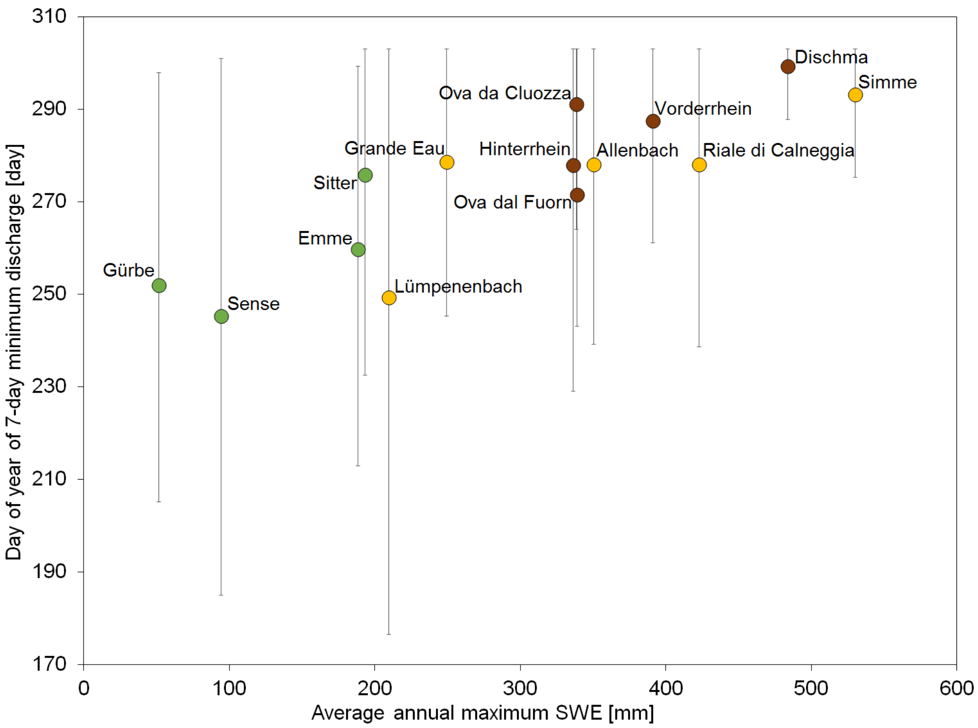

Figure ~~6~~7. Day of year with 7-day minimum discharge against long-term mean annual maximum SWE. ~~Whiskers~~Color circles represent catchment mean and whiskers represent 10% and 90% ~~error bars and small black dots represent minimum~~quantiles. The day of year “1” represents the first day of calendar year (1.1) and ~~maximum.~~day of year “365” represents 31.12. The color of the circle indicates the ~~mean value corresponds~~catchment group according to ~~catchment~~mean elevation (dark brown: ~~highest; dark~~>2000 m a.s.l.; light brown: 1300-2000 m a.s.l.; green: ~~lowest).~~<1300 m a.s.l.).

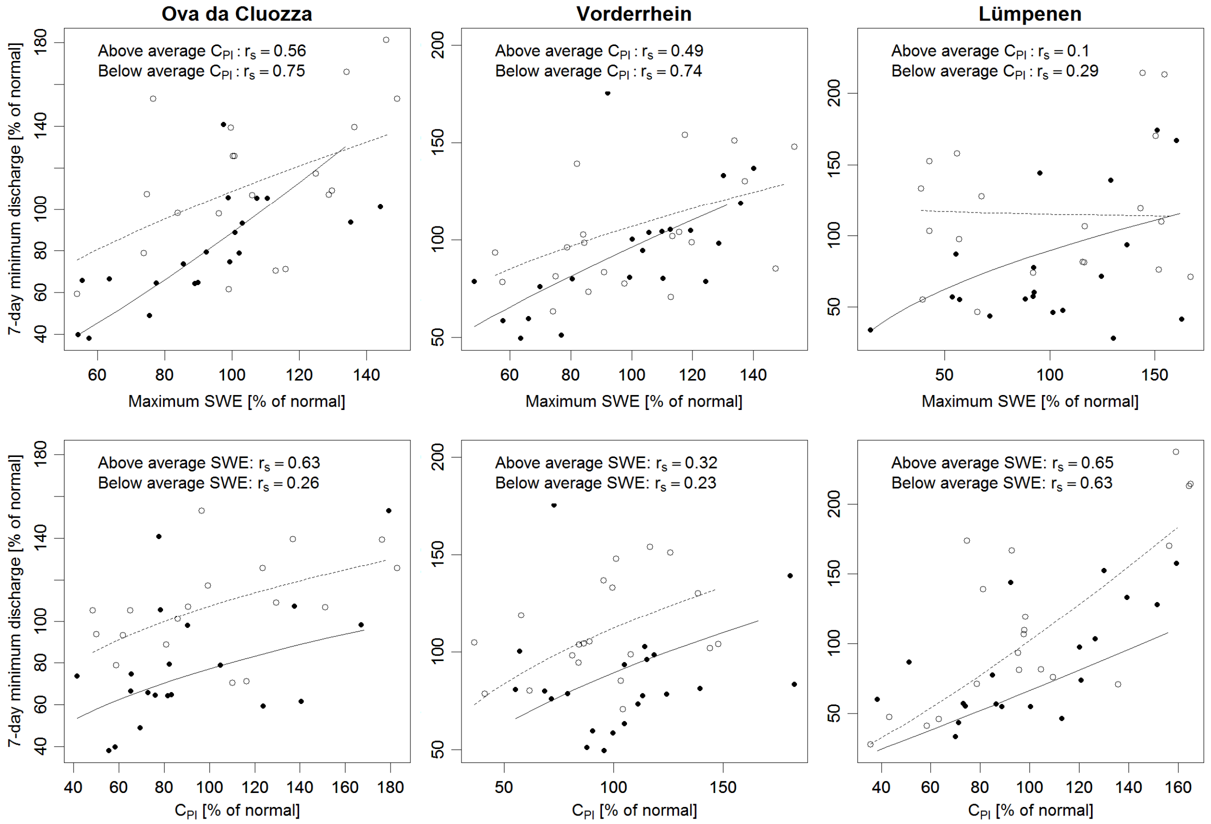

Figure ~~7~~8. Top plots: 7-day minimum discharge in July against maximum SWE for years grouped according to the current precipitation index C_{PI}. Bottom plots: 7-day minimum discharge in July against current precipitation index C_{PI} for years grouped according to maximum SWE. ~~In both cases blue color indicates~~Lines represent the minimum discharge occurring with a 50% probability; r_s represents Spearman rank correlation coefficient. Transparent circles and dashed lines indicate years with above average values and ~~red color indicates~~black points and solid lines indicate years with below average values.

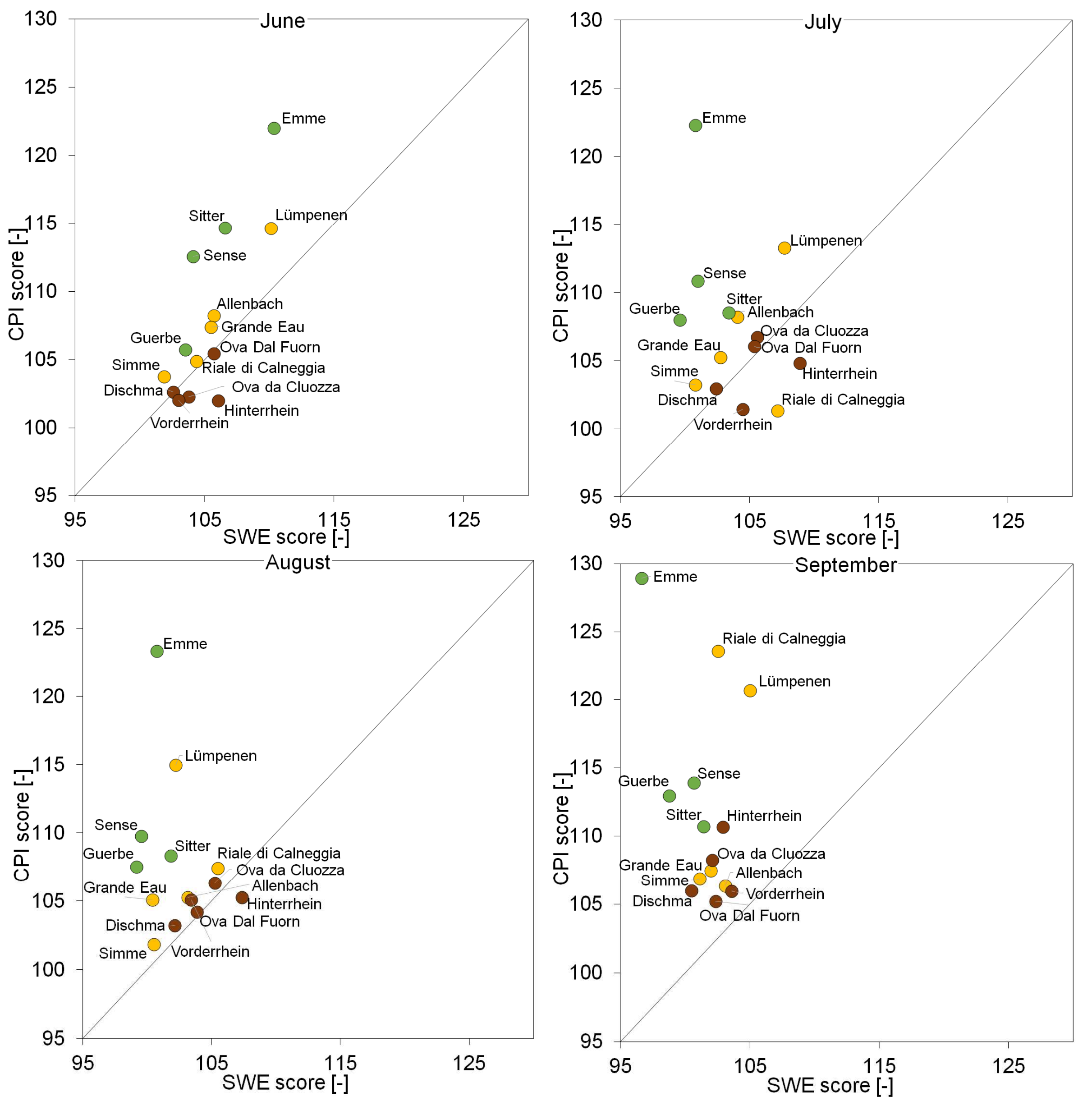

Figure ~~8~~9. Score plots indicating the combined effect of snow and liquid precipitation on low flows in the different months (four plots for June to September). Points below the one-to-one line indicate catchments with a stronger effect of SWE on low flows compared to spring and summer precipitation (expressed as C_{PI}) and vice versa. The color of the ~~symbols~~circle indicates the catchment group according to mean elevation (dark brown: ~~highest; dark~~>2000 m a.s.l.; light brown: 1300-2000 m a.s.l.; green: ~~lowest).~~<1300 m a.s.l.).