Dear Prof. Dr. Sabine Attinger,

We greatly appreciate your efforts with our manuscript and the constructive comments on our manuscript "Quantifying sensitivity to droughts - an experimental modeling approach". Please, find below our response to the comments of the two reviewers (blue, italic). For the revised version we performed new computations, including an analysis to remove the effects snow and an attempt to better use the geological information.

Best regards,
Maria Staudinger (on behalf of the co-authors)

Response to comments of A.F. Van Loon

In this paper the authors simulated the effects of two precipitation scenarios on streamflow, soil moisture, groundwater and drought indices for a number of catchments in Switzerland and analysed the sensitivity of the catchments to drought. They also investigated the main controls on this sensitivity and found that size, elevation and slope were important.

General comments:

My view is that this paper discusses an interesting topic, namely catchment sensitivity to drought and how catchment properties alter the drought signal. However, the research presented in this paper has some serious issues, both related to the methodology and results and the way these are presented. Here I will list the most important ones.

We thank the reviewer for her efforts reviewing our manuscript. We agree on many of the comments and addressing those improved the manuscript as described below. Points where we disagreed are also discussed below.

- The scenarios of 35 year of progressive drying are not realistic. The authors mention that in their discussion but do not make clear why these scenarios are still useful.

We did not mean the drying scenarios to be realistic in the sense of expected climate change, but we argue that the progressive drying scenarios are nevertheless useful as they show the sensitivity of catchments to extreme drying conditions, in particular in relation to the initial conditions (a dry year follows another dry year). With the scenarios that we chose it is possible to include weather conditions that actually occurred in the studied catchments and combine them with drier than ever initial conditions, which are, however, still based on actually observed precipitation data and keeping the observed seasonality. We clarified this in the revised paper.

- The authors did 100 model calibrations and averaged the model results. They do this to avoid choosing the "best" parameter set, but introduce other issues. For example when the timing of peaks is different in the model runs, peaks are smoothed in the ensemble mean. Since this is a study on extremes (drought) this might strongly influence the results. I would suggest using the full ensemble of model results predicting the range of possible scenario effects, instead of taking the ensemble mean or choosing the "best" parameter set.

For ensembles that come from different forcing data we would agree. In this study, however, the ensemble comes from different parameterizations using the same forcing. Choosing the ensemble mean of the simulations derived from different parameterizations has less of a smoothing effect as averaging over different driving data series would have. The advantage of using an ensemble of 100 parameter sets is that this gives a more robust picture (e.g., Seibert and Beven (2009))

- The entire observation period is used for calibration; no validation of the model results is performed. This is not unusual, but for extrapolation outside the calibrated range (as is the case in this research with the two dry scenarios) validation of the model is needed to estimate its robustness in predicting values outside the calibrated range.

While we certainly agree on the need for validation outside calibration conditions when a model is used for prediction purposes (see also Seibert, 2003), we argue that in this study it is preferable to use as much data as possible to best capture the catchment functioning in the calibrated parameter values of the entire period ranging from dry to wet conditions.

- Many of the results are not surprising and not new. For example the "SoYe scenario did not always result in lower streamflow values compared to the longterm mean, but had rather seasons with pronounced lower flows" and the "timing of the pronounced lower flows appeared to occur simultaneously" (p.7669). That a dry year has lower summer values than the long-term mean is to be expected. And the driest year from the reference run and the driest year from scenario SoYe are actually the same year, only with different initial conditions. It is logical that the low flows occur at the same time in the year and that differences between the scenario and the reference run are small because in Swiss catchments the multi-year memory of the hydrological system is low.
We agree that this result is rather confirming than surprising, but the results still provide a novel aspect on the sensitivity of different catchments to extreme drought conditions. However, we shortened this part in the revised version (L199ff).

- On the other hand, the results that are surprising were not further investigated. The conclusion that small, high and steep catchments are less sensitive to drought than large, low-lying and flat catchments is counterintuitive, but it is not based on a thorough analysis. I found serious lacks in the statistical analysis of the results: i) only linear relationships have been tested while from the figure non-linear relationships are apparent, ii) the relationship between the tested variables is not investigated (how much is the added effect of the different variables size, elevation and slope, while high catchments are probably also small and steep?), iii) hydrogeology and land use are only investigated with one variable each although there are many possible factors related to geology and land use that might influence the sensitivity of catchments to drought. Some items really need further investigation, for example the negative effect of size and the influence of storage in snow. In the discussion the authors mention that size was also important in the study by Kroll et al. (2004), but it was not discussed whether size was positively or negatively related to low flows. In Kroll et al. (2004) the inclusion of hydrogeological indices was even more important emphasising the importance of hydrogeology in low streamflow prediction. Which parameters can represent the effect of hydrogeology on drought and low flow is still an important question in drought research, so the authors should focus on this analysis to present some novel results.
Regarding the concerns on the statistical analysis of the results raised by the reviewer we would like to emphasize the following:
i) Actually we did not use only linear relationships but we also used the spearman rank correlation (as described (L...),
ii) This is a valid point, which is addressed in the revised version (L156ff, Table2),
iii) We related several primary measures to investigate possible relationships, but agree that measures for hydrogeology and land use are only investigated with one variable each. We added a test on the potential of the hydro-geological number (L93-97, L254-261, L314-324) in the revised manuscript. Also we further investigated the influence of storage in snow (L175-179, L263-271, L370-374, Figure 8).

- The example of 2003 is not representative for other drought events as this event had a very wet winter and spring as initial conditions for a short intense summer drought (see Stoelzle et al. (2014). Therefore, more than one drought event should be investigated in this type of research.
The purpose of this study was not to investigate several drought types, but a more general sensitivity. By choosing the drought 2003 we wanted to picture the effect of drier initial conditions. As mentioned by the reviewer the summer of 2003 was preceded by a wet winter and spring, which even more underlines the different outcome if it would have been a dry preceding winter and spring. We clarified this in the text (L181-184).

- The paper could benefit from some rephrasing. Sometimes the author's reasoning is hard to follow and at some points I thought the opposite was meant (see some examples below). Due to these issues I would advise to reject this paper, with possibility for resubmission after major reanalysis and rewriting.
We rephrased the text for an easier flow of the argumentation throughout the manuscript.

Specific comments:
- P.7661, l.19-20: "additionally different occurrences" > what do you mean?
We mean that they have additionally different occurrences in time and space, which we clarified in the revised version (L36/37).

- P.7662, l.4: Thanks for citing me, but the correct reference is Van Loon & Van Lanen (2012), full reference: Van Loon, A. F., and H. A. J. Van Lanen (2012), A process-based typology of hydrological drought, Hydrol. Earth Syst. Sci., 16(7), 1915–1946, doi:10.5194/hess-16-1915-2012.
We corrected this in the revised version (L480).

- P.7665, l.1: Since this study focusses on low flow and drought, why not use the Nash-Sutcliffe efficiency based on the logarithm of the discharge?
This is, because we think that the water balance is an important point to be addressed for the general reliability of a hydrological model. We are aware that there are objective functions targeting low flow specifically, but here the choice of a combination of Nash-Sutcliffe and volume error seemed more robust.

- P.7667, l.14-15: Why would you use the days exceeding Q90 if your study is on low flows?
This is done for comparison with the other measures. The information is only the inverse, which should be easy to understand, the resulting indices however are easier to compare. We added a sentence to make this point clear (L146f).

- P.7667, l.15: "respective"?
"Respective" because each of the ensemble member (different parameterization) has its own reference simulation. We clarified this in the revised version (L144)

- P.7667, l.17: Was the Q90 calculated from the reference simulation and then fixed for the scenario runs? If Q90 was recalculated the calculation of change is not correct.
The Q90 was reference simulation and kept for the scenarios as described in the manuscript (L146).

- P.7668, l.14-16: Shouldn't this be opposite? I see the yellow lines closer to 1, so lower ΔQ in wet years.
What is meant is that the higher elevation catchments (yellow lines) compared to the lower elevation catchments (green lines) show a larger change for the wet years at the beginning of the drying scenario. However, after they crossed the 1-line (long term mean) they show a smaller change than the low elevation catchments. We clarified the wording in the revised version (L187-195).

- P.7668, l.19-20: This is only true for scenario SoMo. In SoYe the variability in ΔGW is similar to that in ΔQ.
Correct, but this paragraph talks only about scenario SoMo. We clarified this fact in the revised version (L210).

- P.7668, l.22: "driest year of reference simulation" > driest in terms of P or Q? And which year is it? Is it the same year in the four example catchments?

Driest year in terms of P. It is not the same year for each catchment, which is why it was not mentioned specifically.

- P.7668, l.22-23: Comparison with the long-term mean is not relevant as the driest year from the reference situation is also below the long-term mean.
The scenarios were compared with the long term mean of each DOY (day of year). Depending on the season also the driest year from the reference contains days with higher streamflow than the long term mean.

- P.7668, l.24-26: Not surprising.
As we replied already above, it is not surprising but still worth mentioning.

- P.7669, l.6: Not surprising.
As we replied already above, it is not surprising but still worth mentioning.

- P.7669, l.6-8: I don't think they are so different, probably relative differences are minor. This does not prove differences in sensitivity to drying.
We agree that the differences are small; however, we would not call them minor, at least not for all catchments. It is interesting that the initial conditions can have noticeable impacts even when looking at a whole year. The differences due to initial conditions varied between about 50 and 80%, please note that this is in the same order of magnitude as what might be expected due to climate change (ignoring changing initial conditions). We added discussion on this in the revised version (L289-292).

- P.7669, l.9-11: Not surprising.
As we replied already above, it is not surprising but still worth mentioning.

- P.7669, l.10: Why preceding summer? The initial conditions in this scenario are determined by the preceding years.
Yes, but in the humid climate of Switzerland each real year has anyhow the cycle of snow in winter and some rain in summer. So ultimately the last period before the start of the simulations summer, as of the hydrological year that was used) determines the difference in the initial conditions of the SoMo scenario.

- P.7669, l.14: "diminished"?
Poor formulation indeed, we rephrased in the revised version.

- P.7669, l.17-18: Again the relative differences are not so large.
See above

- P.7669, l.24: "constant days"?
We rephrased and used "fixed" instead.

- P.7669, l.24 & p.7670, l.1: Lower elevation catchments are more vulnerable to drought? This requires more investigation.
We agree that while our results in this study indicate that lower catchments are more sensitive to droughts, further investigations are required. We now assessed the role of snow on runoff vulnerability of lower/higher elevation catchments in an additional sensitivity study (L175-179, L263-271, L370-374, Figure 8).

- P.7670, l.15-17: Is that so? Or is it just hard to see because of the same scale of the y-axis?
This is based on the comparison of the storages for each catchment individually before comparing this relation with the others. So, yes that is so.

- P.7670, l.19-21: Rephrase!
We rephrased this in the revised version.

- P.7670, l.27-28: “IQR” > “Irel”?
Thank you, we changed that.

- P.7671, l.1: Mention prod.no and %forest.
Thank you, we added that.

- P.7671, l.23-27: What do you mean to say here?
We mean that the weather difference between the different years of a catchment should not overprint the catchment properties. We rephrased in the revised version(L345).

- P.7672, l.25-27: ?
It is meant that the higher catchments have some snow component to be considered in late spring and early fall, which influence the streamflow in late summer. We rephrased for clarity (L281-284).

- P.7673, l.20: Here you mention snow as a possible, but the effect of snow should be investigated in detail to make this study valuable. And what are the “greater storages”?
We agree that while our results in this study indicate the effect of snow, more detailed investigations are required. We investigated the effect of snow in a sensitivity study, by systematically modifying the snow influence in each catchment (L175-179, L263-271, L370-374, Figure 8).
Greater storages == potential storage features, such as Moraines, fissures, talus etc.

- Figure 2: Shouldn’t the legend be the other way around (black = SoMo and grey = SoYe)? SoMo was more extreme, wasn’t it?
That is correct, thank you.

- Figure 4: Put the grey line in front of the other lines or make the lines semitransparent. Otherwise it is not visible when the blue line is higher than the grey line. Furthermore, the x-axis is not very clear. Indicate the years that were plotted.
The x-axis is indicating DOY day of year, and hence to us the axis seems very clear.

- Figure 6 and 8: The correlation between some variables is significant, but the relationship is not always clear and linear. Refer to the txt for explanation of prod.no.
Regarding the linearity see response above (rank correlation). We refer now to the explanation of the prod.no., thank you.

References

Stoelzle, M., Stahl, K., Morhard, A., & Weiler, M. (2014). Streamflow sensitivity to drought scenarios in catchments with different geology. Geophysical Research Letters.

Seibert, J., 2003. Reliability of model predictions outside calibration conditions, Nordic Hydrology, 34: 477-492.

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Response to comments of the anonymous reviewer #2

1 Paper Description and General Remarks

The authors investigated the sensitivity of 24 Swiss catchments to meteorological droughts. They constructed two drought scenarios: the first was a modest but constant progression of drying based on sorting the annual precipitation amounts; the second was a more progression of drying based on selecting months from different years to form complete years with the wettest to years with the driest months. The two scenarios are said to retain the intra-annual variability. They deployed the conceptual semi-distributed HBV rainfall-runoff model for their experiments and report varied reactions of catchments to the meteorological droughts showing low levels of streamflow and ground water. In all the studied catchments, they found that mean elevation, slope and size were the main controls on sensitivity of catchment discharge to precipitation: catchments lying at high elevations and having steeper slopes showed less sensitivity to meteorological droughts. Climate change is very important at the present and efforts to improve our understanding of the underlying processes and the probable effects on humanity are highly welcome, thus the relevance of the research. However, I have some remarks that are outlined below.

I could not follow the authors' arguments on many occasions. I propose they streamline their reasoning to eliminate ambiguity.

We agree that there are several statements and formulations in the article that have to be clarified to avoid misinterpretations. We addressed them carefully in the revised version.

The studied scenarios assume progressive future reductions in precipitation, something that is not true everywhere at least not in central Europe (see e.g., Dai (2011)). By the way, 35 years of continuous drying seem unreasonable. It would add credibility if the results from the experiments could be compared to results performed with an observed dataset.

The scenarios that were used in the study were not designed to meet realistic conditions and we are aware that it is unlikely that there is a continuous progressive drying for 35 years. The main idea to develop this method of applying a progressive drying was to see the sensitivity of different initial conditions (dry follows drier) and the different reactions of the catchments to the different initial conditions.

However, the way the precipitation data was used to create the scenarios ensured that the scenarios still showed the observed seasonality as the observed data.

Secondly, the different catchments should react differently to forcings but the authors do not mention the years when the various catchments were under drought. Apart from the summer drought of 2003 falling within the simulation period (the selection of which could have been motivated by data availability considerations), what else qualifies the event as representative?

The summer of 2003 was an event that was affecting all of the catchment of this study and it is mentioned as the summer drought that could be expected in the future (Schär, 2004). The event of 2003 is qualified in fact by the period in which it falls, motivated by data availability. For several catchment also the drought of 1976 would have been available but not for all. To include as many catchments as possible for inter catchment comparison we decided to take only 2003 as an example. We clarified our motivation in the revised version (L163-165).

A sustained reduction in precipitation would have an impact on temperature: there would be less water to evaporate, thereby an increase in the air temperature and thus an amplification of drought severity (see e.g. Trenberth et al. (2014)). Sheffield et al. (2012) studied the combined effect of reduced precipitation and increased temperature and decoupling the two might be an oversimplification. Much as that might be beyond the scope of the current work, I would have loved the authors to state, at least speculatively how their chosen scenarios impact the energy balance and ultimately the partitioning of soil moisture.

It is true that there might be feedback that could not be considered in the simple approach taken. However, we did not de-couple the observed temperature and precipitation as we used the air temperature and precipitation record that was observed at a certain time and did not split them. We added some discussion on this important point in the revised version (L364-369).

It is possible that the scope of the experiments was not sufficient for all the conclusions to be drawn. Specifically, I'm not convinced that the subsurface properties do not have any bearing on the groundwater storage. I also find issues with the way the authors remained silent on the changes in land cover (or land use) over the simulations period.

We agree that the subsurface should have an influence and we saw it in the example of 2003 that the modeled subsurface storages of different catchments reacted differently. However, we did not find a relation to the simple hydro-geologic measure that we derived from hydrological maps. We clarified this in the revised version and added an investigation of the role of the assignment of the numerical number (L93-97, L254-261, L314-324).

Regarding the land cover or land use change over the simulation period, we indeed did not consider this. Our approach was looking at the sensitivity of catchments to the continuous drying. We assume that e.g. trees would respond to the continuous drying and of course this would affect evapotranspiration rates and runoff behavior. As in the comment above about feedback related to different temperatures, we will add discussion on this point. It should be kept in mind, however, that also in many other scenario studies there is no change in vegetation included but only the response to decreased precipitation or increased temperature analyzed. In addition, land use changes in the last 40 years in Switzerland in the selected catchments were very moderate, since we selected headwater catchment with a low proportion of urbanization.

2 Specific Remarks

P7661, L14 ...sensitivity of course results from... modification by specific catchment properties. It is rather counter-intuitive that hydrogeological catchment characteristics have no effect at all on groundwater droughts. Could it be possible that the experiments conducted are not adequate for such a conclusion to be drawn.

See discussion above.

7661, L15 Please write an individual instead of a individual.

Ok.

P7661, L26 Please insert a comma after Further.

Ok.

P7666, L6 Please consider rewriting the sentence as Δx was calculated using Eq. 2 for ... (GW+SUZ+SLZ) as shown in Fig. 1. Numbering for line 5 seems to be misplaced.

The groundwater storage used in the study is indeed the sum of the two groundwater storages (SUZ and SLZ) of HBV. The line numbering is generated automatically using the template of HESSD.

P7666, L10 Insert a space before IQR.

Ok

P7669, L11 Please rephrase to ... scenario SoMo always resulted in ...

Ok

P7669, L27 Please change a difference to the difference. I suppose you use talking about flow rating curves and the probability of exceedence here. Since your study is on droughts (low flows), it might be confusing to some people when you speak of days exceeding Q90. I suggest you briefly say something to that effect in order to mitigate the potential source of confusion.

As mentioned in the response to the review to the other reviewer, the switch from days below to days exceeding was done to compare the different measures more easily. We clarified this in the revised *version (L146f).*

P7670, LL8-17 Can the results presented in Fig. 5 be reproduced when the model is allowed a reasonable spin-up period?

For the results in Figure 5 we already applied a year of warm up, which we made clear in the revised Version (L115).

P7670, section 3.3 The authors state that small, high and steep catchments are less sensitive to drought than large, low-lying and at catchments. Could the authors offer an explanation why this is so and how the sensitivity of large, highland catchments might be? I also expected the changes in land use to be relevant to the evapotranspiration from the catchments. Could the authors say if the land use (or cover) was constant (and if so, why) over the entire period?

See discussion above. We clarified this in a revised version (L129-131, L364-370).

P7672, L9 I think that disregarding the initial wetness destroys the autocorrelation structure of the groundwater signal (long memory effects are known to exist in some regions).

The phrasing was maybe ambiguous and we clarified in the revised version. The initial wetness was not considered for construction of the scenarios, i.e. there might have been a dry year with a wet end of the year. It anyhow would have been sorted as a dry year closer to the end of the scenario as of the sorting by precipitation means only. Before we ran the scenarios the model was calibrated to observed data (in natural sequence). The modeled storages of the catchments should ideally be sized to represent memory capacity.

P7687 Please make the figures bigger and print the axis labels labels close to the corresponding graphics.

We worked on increasing the readability of the figures.

The authors did not aim to construct realistic scenarios and intentionally removed the natural variability in precipitation. Since some of the results are rather surprising, it might be helpful to perform their experiments with an observed data-set.

The natural variability of precipitation was not removed, neither for the yearly or the monthly scenarios. For the SoYe scenario the years were sorted from wet to dry, however the intra-annual variability as it was observed remained. Also for the more extreme scenario SoMo the intra-monthly variability was actually observed, i.e. its natural climatic regime.

Their arguments were also hard to flow and most of them need reformulating. For these, I recommend a major revision before the manuscript is accepted for publication.

We reformulated the text to improve its readability.

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Sheffield, J., Wood, E. F. and Roderick, M. L. (2012), `Litle change in global drought over the past 60 years', Nature 491, 435-438.

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Quantifying sensitivity to droughts - an experimental modeling approach

M. Staudinger[1], M. Weiler[2], and J. Seibert[1,3]

[1]Department of Geography, University of Zurich
[2]Chair of Hydrology, University of Freiburg
[3]Department of Earth Sciences, Uppsala University, Sweden.

Correspondence to: M. Staudinger
(maria.staudinger@geo.uzh.ch)

Abstract. Meteorological droughts like those in summer 2003 or spring 2011 in Europe are expected to become more frequent in the future. Although the spatial extent of these drought events was large, not all regions were affected in the same way. Many catchments reacted strongly to the meteorological droughts showing low levels of streamflow and groundwater, while others hardly reacted. ~~The~~ Also the extent of the hydrological drought for specific catchments was ~~also~~ different between these two historical events due to different initial conditions and drought propagation processes. This leads to the important question of how to detect and quantify the sensitivity of a catchment to meteorological droughts. To assess this question we designed hydrological model experiments using a conceptual rainfall-runoff model. Two drought scenarios were constructed by selecting precipitation and temperature observations based on certain criteria: one scenario was a modest but constant progression of drying based on sorting the years of observations according to annual precipitation amounts. The other scenario was a more extreme progression of drying based on selecting months from different years, forming a year with the wettest months through to a year with the driest months. Both scenarios retained the ~~typical~~ observed intra-annual seasonality for the region. ~~The~~ We evaluated the sensitivity of 24 Swiss catchments to these scenarios ~~was evaluated~~ by analyzing the simulated discharge time series and modeled ~~storages~~storage. Mean catchment elevation, slope and ~~size were found to be~~ area were the main controls on the sensitivity of catchment discharge to precipitation. Generally, catchments at higher elevation and with steeper slopes ~~seemed to be~~ appeared less sensitive to meteorological droughts than catchments at lower elevations with less steep slopes.

1 Introduction

Meteorological droughts such as the summer drought of 2003 (Rebetez et al., 2006) or the spring drought of 2011 (Kohn et al., 2014) in Europe caused low water levels in lakes, rivers and groundwater. Generally, a prolonged lack of precipitation (meteorological drought), storage of precipitation as snow or a strong deficit in the climatic water balance can propagate through the hydrological system causing soil moisture drought and hydrological drought (Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010). The consequences of such droughts are challenging: water use restrictions have to be applied to, for instance, energy production or irrigation. Water quality can be affected by faster warming of less than usual water and reduced dilution, which in turn becomes an issue for ecology, but also for drinking water supply. Droughts like those in 2003 and 2011 are predicted to become more frequent in the future (Solomon, 2007), which calls for a better understanding of the ~~reaction~~ response of different systems to droughts. Focusing on single processes in one catchment allows for a detailed analysis of ~~processes occurring or not occurring during a~~ the occurrence of different processes during an individual drought event (Santos et al., 2007; Trigo et al., 2010; Li et al., 2010). However, there are not enough observations of historical drought events to perform such a detailed analysis for several events and catchments with resulting detailed links between cause and effect. Historical droughts usually differ in initial conditions regarding the general preceding wetness and often additionally different occurrences in time and space, which makes a spatial and temporal analysis extremely challenging. A meteorological drought can develop into a hydrological drought through different mechanisms that are controlled by catchment characteristics as well as climate ~~(Eltahir and Yeh, 1999; Peters et al., 2003; Tallaksen and Van Lanen, 2004; ?)~~ (Eltahir and Yeh, 1999; Peters et al., 2003; Tallaksen several consecutive meteorological droughts can turn into a combined and prolonged hydrological drought and they can be attenuated by the ~~storages~~ storage of a catchment. Further~~there is often a varying~~ , a time lag between meteorological, soil moisture and hydrological drought ~~that involves~~ affects both streamflow and groundwater ~~(?)~~ (Van Loon and Van Lanen, 2012) . In addition to a deficit in precipitation, ~~droughts can also be caused by temporary storage of water as ice or snow (Van Loon et al., 2010)~~ also ice and snow acting as temporary storage can cause droughts (Van Loon et al., 2010) . Observed droughts reflect the diversity of drought processes which led to varyingly strong responses on meteorological droughts in different regions and catchments. ~~This diversity is reflected in the observed droughts , where not every region and catchment was affected similarly in severity and manner.~~ Based on the ~~different~~ various drought generating mechanisms, ~~Van Loon et al. (2010)~~ Van Loon and Van Lanen (2012) developed a general hydrological drought typology and distinguished between six different drought types that include the type of precipitation and air temperature conditions preceding the drought (classical rainfall deficit drought, rain-to-snow-season drought, wet-to-dry-season drought, cold-snow-season drought, warm-snow-season drought, and composite drought).

Previous studies looked at historical droughts and tried to link the occurrence and temporal development of a drought with climate and catchment characteristics such as ~~, for instance,~~ topography or geology ~~(e.g. Stahl and Demuth, 1999; Zaidman et al., 2002; Fleig et al., 2006)~~ (e.g., Stahl and Demuth, 1999; Zaidman et al., 2002; F Stahl and Demuth (1999) found that spatial and temporal variability of streamflow drought was influenced by the geographical and topographical location and the underlying geology. Periods of prolonged streamflow drought were ~~found to be caused by the~~ linked with persistent occurrence of specific circulation patterns, however~~no clear link between~~ , temporal streamflow drought development ~~and~~ could not be linked to observed climatic drought~~was found~~.

Many studies have used scenarios to estimate the impact of climate change on streamflow in general and some ~~that~~ focus on droughts in particular ~~(e.g. Wetherald and Manabe, 1999, 2002; Wang, 2005; Lehner et al., 2006)~~ (e.g., Weth The usual approach is to use simulations of general circulation models or regional climate models (GCM/RCM) with plausible scenarios of greenhouse gas emissions to drive hydrological models. However, there are large uncertainties connected to the GCM and RCM simulations and the choice of bias correction method (Teutschbein and Seibert, 2012, 2013), and the range of resulting impacts is accordingly high. Wilby and Harris (2006) used different GCMs, emission scenarios, downscaling techniques and hydrological model versions to assess uncertainties in climate change impacts and found that the resulting cumulative distribution functions of low flow for the river Thames were most sensitive to uncertainties in climate change scenarios and downscaling. Instead of dealing with these large uncertainties, here we focus on systematic changes. Thus, scenarios that exclude the large sources of uncertainty (climate change scenarios and downscaling) are ~~needed~~ a straightforward way to investigate the different ~~reactions~~ responses of catchments to droughts.

In this study we ~~address~~ assess how sensitive different catchments are to meteorological droughts and whether this sensitivity can be linked to a specific type of catchment, classified by catchment characteristics. We aim to answer these questions using a modeling experiment with two different scenarios of ~~increasingly~~ progressively drier meteorological conditions, based on observations.

2 Methods and Data

2.1 Data

We selected 24 Swiss catchments, which vary in ~~size~~area, mean catchment elevation, land cover and geology (Table 1). ~~To investigate the main natural underlying processes, only~~ Only catchments with minor anthropogenic influence were selected, i.e. no catchments with dams, major water extractions or inflow of sewage treatment plants~~. Additionally, the~~ , to investigate the main natural underlying processes. The selected catchments have, if any, minimal glacier influence and have discharge stations of satisfactory precision during low flow. Daily discharge observations were provided by (FOEN, 2013a). Gridded temperature [°C] and precipitation [mm] data (Frei, 2013) available for Switzerland (MeteoSwiss, 2013) were averaged over each catchment and then used to force the hydrological model. The observation period for discharge data used in this study extended from 1993 to 2012, for the meteorological data from 1975 to 2012. ~~Size~~Information about catchemnt area, mean catchment elevation, forested land cover, and slope were extracted from the digital elevation map of Switzerland (25 m resolution).

A hydrogeological productivity number, which is a measure of hydraulic conductivity and thickness of the aquifer, was derived from the vulnerability map of Switzerland (Spreafico et al., 1992): first, features of the aquifers were classified as productivity: high, variable, low, ~~zero. We~~ very low. Then, we assigned a numeric value between zero and one to each of these productivity classes (high: 1, variable: 0.5, low: 0.1, very low: 0) and computed an area-weighted mean. In a second step we investigated the influence of the choice of the numeric values by calibrating the values of the productivity classes to maximize the correlation between area-weighted mean values and sensitivity measures (described in the following section). The calibration was conditioned so that values increased from low to high productivity.

2.2 HBV modeling experiment

~~For~~ We conducted the modeling experiment ~~we used~~ with the semi-distributed conceptual HBV model (Bergström et al., 1995; Lindström et al., 1997)~~with~~, in the version HBV light (Seibert and Vis, 2012). ~~In this study the catchments were separated into~~ Each catchment consisted of several elevation zones of 100 m. The HBV model uses different routines (Figure 1) to simulate catchment discharge based on time series of daily precipitation and air temperature as well as estimates of long-term monthly potential evapotranspiration~~. The routines in HBV include the following~~:

- Snow routine: snow accumulation and melt are computed by a degree-day method including snow water holding capacity ~~as well as~~ and potential refreezing of melt water.
- Soil routine: groundwater recharge and actual evaporation are simulated as functions of the actual water storage in the soil box. The soil moisture storage is called SM.
- Response routine: runoff is computed as a function of water storage in an upper and a lower groundwater box. The groundwater storage (GW) from both groundwater boxes was summed.
- Routing routine: a triangular weighting function routes the runoff to the outlet of the catchment.

Detailed descriptions of the model can be found elsewhere (Bergström et al., 1995; Lindström et al., 1997; Seibert, 1999). The HBV-light model was calibrated automatically for each of the catchments over the period 1993 to 2012 using a genetic optimization algorithm with subsequent steepest gradient tuning (Seibert, 2000). Parameter uncertainty was addressed by performing 100 calibration trials, which resulted in 100 optimized parameter sets according to a combination of Nash Sutcliffe model efficiency and volume error (F_{LS}, Eq. 1 (Lindström et al., 1997)), where the weighting factor for the latter was set to 0.1, as recommended by Lindström et al. (1997); Lindström (1997). F_{LS}

ranges between minus infinity for poor fits and 1 for a perfect fit,

$$F_{LS} = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2} - 0.1 \frac{\sum |(Q_{obs} - Q_{sim})|}{\sum Q_{obs}} \tag{1}$$

One simulation was run ~~for each of the parameter sets~~ per parameter set over the entire meteorological observation period~~and the~~. The simulation results of this ensemble ~~of the~~ (100 selected parameter sets) were averaged at each time step to derive the reference simulation. The same ~~procedure was performed~~ was done for the scenarios. Each model simulation was preceded by a one year warm up period.

2.3 ~~Scenario construction~~Construction of the scenarios

~~Two~~ We constructed two precipitation time series ~~were constructed as~~ as purely hypothetical scenarios, over the period 1975 to 2012, with progressively drying conditions:

- Scenario with sorted years (SoYe): All years over the meteorological observation period were sorted from the wettest to the driest year according to the total annual precipitation. Thus, a scenario of modest but continuous progression of drying was ~~constructed~~derived.

- Scenario with sorted months (SoMo): For this scenario we shuffled the individual months, with the wettest January together with the wettest February, and so on forming the first year. The second wettest individual calendar months composed the second year. With this approach a scenario was created with a continuous progression of drying in a more extreme manner than SoYe, but ~~still~~ nevertheless keeping the natural seasonality.

The daily air temperature matching the precipitation from the original time series was re-arranged in parallel to the precipitation scenarios~~.~~, i.e. the observed temperature remained linked to the observed precipitation. For all scenarios the land cover was kept unchanged allowing to focus on the sensitivity of response of streamflow by gradually drying out the catchment. The land cover also remained basically unchanged in the last 40 years in the studied catchments. These hypothetical scenarios showed the sensitivity of catchments to extreme drying conditions, in particular in relation to initial conditions (one dry year follows another). The scenarios allow further to include observed weather conditions combined with drier than ever observed initial conditions, that are still based on observed preceding precipitation.

2.4 Relative change to long-term conditions

First, we looked at the relative change of each scenario year, x_i, to the long-term mean of the reference simulation, $\overline{x}$.

$$\Delta x_i = \frac{x_i}{\overline{x}} \tag{2}$$

where x stands for the variable of interest, and i the year. ~~Δx~~ Δx_i was calculated for simulated runoff (Q_{sim}), simulated soil moisture storage (SM), and the combined simulated upper and lower groundwater storages ($GW = SUZ + SLZ$) (Fig. 1) (Eq. 2). Secondly, to assess the catchment sensitivity to the progression of drying we calculated the inter-quartile range (IQR) of ~~Δx~~all Δx_i. IQR represents the variability during the drying phase~~and since~~. Since the scenarios force progressive drying over the course of the years ~~,~~ IQR can be seen as a measure of sensitivity to droughts: the smaller the value of IQR, the less sensitive a catchment is to droughts, and the higher the value of IQR, the more sensitive a catchment is to droughts. This sensitivity ~~of course~~ results from both the local climate variability and modification by specific catchment characteristics. Since the construction of the scenarios was based on annual and monthly precipitation differences, we accounted for the relative influence of the inter-annual variability of precipitation in each catchment on the scenario. For each year the ratio between mean annual precipitation P and long-term mean annual precipitation $\overline{P}$ was calculated (Fig. 2). This precipitation ratio was ~~used in the further analysis~~ then used to account for the potential influence of the inter-annual precipitation variability~~to enable a comparison between the different catchments. To minimize the influence of the local precipitation variability each~~. Each IQR was divided by the inter-quartile range of these precipitation ratios (Eq. 3) to minimize the influence of the local precipitation variability and to compare between the different catchments. The so modified IQR is referred to as I_{rel}.

$$I_{rel} = \frac{\Delta x_{75} - \Delta x_{25}}{\frac{P}{\overline{P}}_{75} - \frac{P}{\overline{P}}_{25}} \tag{3}$$

where Δx_{75} is the 75^{th} percentile of ~~Δx~~ Δx_i and Δx_{25} the 25^{th} percentile of ~~Δx~~Δx_i. Even though ~~this~~ I_{rel} includes both wet and dry years, it gives an overall impression of the ~~reaction~~ response of a catchment to the progression of drying. We ~~also compared the extreme~~ accounted for drought more specifically by comparing the extreme dry end of each scenario (driest year of both scenarios) with the long-term mean~~to account for drought more specifically~~. The extreme end of each scenario was additionally compared to the driest year from the reference simulation in order to determine in which seasons the strongest effect of drying was found. ~~Further, to find catchment controls on the sensitivity of catchments to droughts, we analyzed the correlations between specific catchment characteristics (Table 1) and sensitivities. The correlations were calculated using the Spearman rank correlation to detect rank correlations between catchment characteristics and sensitivities. The significance of the correlations was evaluated using the p-value of the distributions, where correlations with a p-value of <0.05 are considered significant.~~

~~To target~~ We looked at drought characteristics more specifically ~~, we counted~~ by counting the days per year that exceeded the ~~90^{th}~~ 90^{th} streamflow percentile (Q_{90}) of the respective reference simulation (100 parametrizations). Q_{90} is a commonly used threshold value to define hydrological drought periods. Again, we calculated a relative change (Eq. 2), here with ~~the exceedance days of~~ x being the number days exceeding Q_{90}~~as x. Other indices describing the~~. We used days exceeding Q_{90} instead of days below the threshold, to derive indices that are larger, when the sensitivity is higher. We used further indices that describe the influence of the progression of drying at its extreme dry end~~,~~. These indices are the ratios of the ~~mean~~ difference between long-term mean and mean of the driest year of each scenario and the long-term mean ($\Delta Q_{DriestSoYe}$ for scenario SoYe; $\Delta Q_{DriestSoMo}$ for scenario SoMo). ~~The smaller these indices~~As for the other indices, the larger $\Delta Q_{DriestSoYe}$ and $\Delta Q_{DriestSoMo}$ are, the more sensitive the respective catchments are to droughts.

~~Further, we studied the summer of 2003 as one of the historical droughts that falls in the observation period of this study in another simulation experiment making use of the~~ Catchment controls on the sensitivity of catchments to droughts were investigated by correlations between specific catchment characteristics (Table 1) and sensitivities using Spearman rank correlations. The significance of the correlations was evaluated using the p-value of the distributions, where correlations with a p-value of $<$0.05 were considered significant. An important aspect in such analyses are correlations among catchment characteristics themselves, which can make an interpretation of correlations between catchment characteristics and sensitivities more difficult. For our catchments, even though there was a significant correlation between mean catchment elevation and slope (Table 2), the highest elevation catchments do not have the steepest slopes.

The influence of drier initial conditions was highlighted in a further simulation experiment based on scenario SoMo. ~~Here,~~ We chose the drought in 2003 because it was one of the recent serious summer droughts that affected all studied catchments and this summer drought had a normal preceding winter, i.e. normal snow conditions. Recent droughts in spring (e.g., 2011, 1976) were not analyzed more specifically, as these droughts had already particularly dry initial conditions. For this simulation experiment, we used the last years of the scenario SoMo up to the end of May followed by the actual series of summer 2003 starting from 1 June. In this way ~~for each catchment~~ we simulated how much more ~~the~~ each catchment would have been affected if the preceding months to the 2003 drought event would have been drier than ~~in the actual observation~~actually observed. For all catchments a further index was calculated describing the sensitivity of the catchments to drier initial conditions and thus also to droughts by dividing the mean of the SoMo scenario based simulation with the drier initial conditions for the summer months of 2003 (June-August) by the mean of the reference simulation for the same months. This index was called ΔQ_{2003} for $Qsim$, ΔSM_{2003} for SM, and ΔGW_{2003} for GW. The ~~smaller~~ larger these indices are, the ~~less~~ more sensitive the respective catchments are to droughts.

The sensitivity of the catchments, as described by the introduced indices, was further analyzed with regard to the role of snow therein. The question was, how much of the sensitivity could be attributed to snow storage? We investigated this by simulating all precipitation as rain (i.e. no snow accumulation) using the same parameter sets derived by the calibration and repeating the scenario analyses described above.

3 Results

3.1 Inter-annual variation

All catchments could be calibrated satisfactorily with median F_{LS} values (Eq. 1) ranging between 0.73 and 0.92 (Table 1). The relative change of the different variables clearly indicated a progression of drying of streamflow as well as of the storages, where the relative change of the continuous drying for all catchments was smallest for SM for both scenarios (Figure 3).

The SoMo scenario generally resulted in stronger responses to the drying and the relative changes specific for the different catchments became more pronounced than in scenario SoYe. ~~For the catchments located at higher elevations, larger~~ During wetter conditions than the long-term mean the Δ_{Qsim} values were ~~found for values greater than one (wetter conditions than the longterm mean)~~ larger for the higher elevation catchments compared to lower elevation catchments. During drier conditions than the long-term mean, the Δ_{Qsim} values ~~of the catchments with higher elevations were smaller~~ were smaller for the higher elevation catchments compared to lower elevation catchments. This indicates that during wet conditions the high elevation catchments were more sensitive to the progressive drying, however during dry conditions high elevation catchments were less sensitive to the drying compared to lower elevation catchments. The same can also be seen for Δ_{GW} where the change from wetter ~~(above 1) to drier (below 1)~~ to drier conditions relative to the ~~longterm~~ long-term GW mean shows more variability between the catchments than ~~for~~ Δ_{Qsim} (Figure 3).

The general behavior ~~was shown using four catchments as examples~~ at the end of the scenarios was illustrated using four of the catchments by comparing the long-term mean and the driest year of the reference simulation (in terms of precipitation) (Figure 4). Scenario SoYe resulted, most of the time, in streamflow values below the long-term mean. However, the scenario did not always result in lower streamflow values compared to the long-term mean~~, but had rather seasons with pronounced lower flows: this was the case in fall/winter as well as in summer, where the hydrograph of the SoYe scenario falls entirely below the long-term mean for the pluvial Mentue catchment~~. For the nival catchments (Ilfis, Sitter, Emme) the hydrograph from SoYe was below the long-term mean streamflow during the spring flood as well as during late summer. ~~However, the~~ The difference between long-term mean streamflow and the streamflow from scenario SoYe varied remarkably between the catchments~~although the timing of the pronounced lower flows appeared to occur simultaneously~~. The overall difference between the long-term mean and the scenario SoYe ~~, which can be seen in the cumulative sums, confirms this~~ (cumulative sums) confirms the variation between the catchments and thus the variation in their sensitivity to ~~the~~ continuous drying (Figure 4). The difference between the last year SoYe and the driest year of the reference simulation was minor and resulted from the different initial conditions ~~given~~ caused by the preceding summer~~and was very small~~. The driest year of scenario SoMo resulted ~~always~~ for each day in streamflow values below the long-term mean~~as well as below~~ , the driest year of the reference simulation and the driest year of the SoYe scenario for all catchments. ~~For~~ The discharge of the pluvial Mentue catchment ~~discharge nearly diminished for~~ was nearly zero in the driest year of ~~the scenario~~ scenario SoMo. For the catchments with some snow influence ~~there are~~ remained periods of higher streamflow in spring and summer, however with a very reduced spring flood as compared to the SoYe scenario or the ~~longterm mean~~reference. For the scenario SoMo, the cumulative sums show that the annual difference between long-term mean and the scenario varies ~~for~~ among the different catchments.

3.2 Low flow frequency

The ~~relative difference of the~~ frequency of days ~~that were~~ exceeding the Q_{90} threshold ~~was small~~ changed only little for the SoYe scenario (Figure 3) compared to the long-term mean. Even though over the course of the years a slight decrease of days exceeding ~~the threshold~~ Q_{90} could be noticed, there were still years at the end of the scenario that had ~~longer durations of~~ more exceeding days than the ~~longterm mean. Note, that the upper boundary is given by the constant days that are exceeding Q_{90} per year and the maximum days per year.~~ long-term mean. For the SoMo scenario, however, there ~~is~~ was a strong decrease in days exceeding ~~the~~ Q_{90} ~~threshold~~ with the progression of drying. In this scenario ~~a~~ the difference between the catchments also became apparent: in the relatively wetter years, the lower elevation catchments already ~~start~~ started to have less days above the threshold, i.e. are more vulnerable to droughts. In the medium dry years of the scenario the higher elevation catchments also ~~show~~ showed less days above the threshold compared to the long-term mean. The highest elevation catchments ~~follow~~ followed in even drier years of the scenario to show less days above the threshold compared to the long-term mean. In ~~comparison to scenario SoYe, in scenario~~ scenario SoMo, the highest elevation catchments show a clear decrease in days ~~above~~ exceeding the Q_{90} threshold at the dry end of the scenario.

3.3 Initial conditions

The historical drought event of the summer 2003 and how it would have changed with different initial conditions for the different catchments is shown for the four example catchments (Figure 5). While for the Mentue, Ilfis and Sitter catchments the influence of the drier initial conditions can be seen relatively long into the summer months, for the Emme catchment, this memory is comparably short. However, looking at the storages SM and GW for the reference simulation as well as the simulation with drier initial conditions shows that the causes for longer or shorter influence are not the same for the different catchments: the important storage for the effect of the initial conditions for Mentue and Ilfis is composed of both storages, while for the Sitter and the Emme catchments SM seems to be stronger and important for longer than GW.

3.4 Importance of catchment characteristics

The ~~comparison of the~~ I_{rel} values ~~, as a measure of sensitivity to droughts, with simple catchment characteristics showed, for~~ of Q_{sim} ~~, significant correlation between the I_{rel} values and catchment~~ were significantly correlated with catchment mean elevation, size and slope, respectively (Figure 6). Mean catchment elevation and drought sensitivity were ~~correlated with~~ negatively correlated, i.e. higher mean catchment elevations were related to lower drought sensitivities. Steeper slopes are also related to lower drought sensitivities. ~~Even though there was a significant correlation between mean catchment elevation and slope, the highest elevation catchments do not always have the steepest slopes. Hence, it makes sense to look at both slope and mean catchment elevation individually.~~ For SM the ~~IQR~~ I_{rel} values were significantly correlated with size and slope, while for GW the IQR values were correlated with mean catchment elevation and slope. The ~~variables describing hydrogeology as well as land cover~~ percentage of forested area had no significant influence on the sensitivity of the catchments ~~studied to droughts.~~ to droughts, while the hydrogeological productivity numbers were only significantly correlated with the IQR of days exceeding Q_{90} (Figure 6). A summary of all indices can be found in Table 3. The drought targeting indices (IQR of days ~~above the threshold~~ exceeding Q_{90}, $\Delta Q_{DriestSoYe}$, $\Delta Q_{DriestSoMo}$, and changes of summer 2003 with drier initial conditions ΔQ_{2003}, ΔSM_{2003} and ΔGW_{2003}) could also be related to the catchment characteristics (Figure 7); most of them were correlated with size, elevation or slope of the catchment: IQR of days ~~above the threshold,~~ exceeding Q_{90} as well as ΔQ_{2003}, were significantly correlated with size and slope of the catchment. The ratios of the driest years of the two scenarios $\Delta Q_{DriestSoYe}$ and $\Delta Q_{DriestSoMo}$ were significantly correlated with size and elevation, respectively. ΔSM_{2003} was correlated with mean elevation, slope and size of the catchment.

4 ~~Discussion~~

~~In the analysis of the simulations from the scenarios, which clearly depend on the inter-annual variability of precipitation for each catchment, we removed the effect of precipitation variability by dividing the IQR values by the inter-quartile range of the precipitation ratio. Following many studies that document the sensitivity of streamflow to climate and climate change, Schaake et al. (1990) , Dooge (1992) , and Sankarasubramanian et al. (2001) introduced and applied the so called streamflow elasticity, which describes the sensitivity of streamflow to precipitation. The streamflow elasticity was developed as a robust, unbiased approach that on average and over many applications might discern the true sensitivity of streamflow to climate (Sankarasubramanian et al., 2001) . Similar to our approach, the streamflow elasticity is calculated by taking annual streamflow and precipitation into account (Sawicz et al., 2011) . For the comparability of the sensitivity to the drying in our approach instead we ensured that the streamflow elasticity did not influence the results of the scenario simulations in a manner that would make it impossible to see any influence due to specific catchment~~

~~characteristics other than precipitation.~~

~~The scenarios were constructed by applying sorted annual or monthly precipitation, while air temperature was not considered explicitly. For example Null et al. (2010) considered air temperature and analyzed streamflow and particular lowflow sensitivities to climate change by using scenarios with increased temperatures, but constant precipitation for mountain catchments. However, the results of previous case studies considering total streamflow response to changes in precipitation and temperature indicated that future total streamflow is more sensitive to precipitation than to temperature (Lettenmaier et al., 1999; Nijssen et al., 2001) .Anot issue related to the construction of our scenarios is that the preceding wetness of the season was not considered while sorting. This could lead to actual drier or wetter initial conditions for the following year than indicated by the annual sum, particularly for the SoYe scenario. We tried to minimize this effect by using hydrological years starting on October 1,~~ The correlation between hydrogeology (expressed in productivity numbers) and drought sensitivity was influenced by the choice of the numeric values of the productivity classes. The correlation between hydrogeology and drought sensitivity could be increased from not significant correlations to Spearman rank correlation coefficients of 0.53. The correlation that existed between productivity number and days exceeding Q_{90} could be increased to 0.5 compared to 0.4 of the originally assigned values for each productivity class. The values for the productivity classes after calibration to the different drought sensitivity indicators were high: 0.79-0.97, variable: 0.29-0.6 ,low: 0.22-0.24 and very low: 0.02 -0.22.

3.1 Role of snow

Repeating the scenario simulations with rain instead of snow resulted in only minor changes of the sensitivities of the catchments (Figure 8. For $I_{rel}Qsim$ the higher catchments were slightly more sensitive to the progressive drying without snow storage, however the change in sensitivity was not systematically increasing with the percentage of snow observed in the catchments. The changes in $I_{rel}GW$, $I_{rel}SM$ and IQR of days exceeding Q_{90} when simulating no snow were similar, with higher elevation catchments being more sensitive without snow. However, for $\Delta Q_{DriestSoYe}$ and ~~not calendar years. Still, there could have been a dry summer in an otherwise relatively wet year which then serves as initial conditions for the following year. However the effect should be low compared to a start in winter with, for instance, a large snow cover at the end of an otherwise dry year.~~ $\Delta Q_{DriestSoMo}$ there are very small changes in sensitivity for all catchments in both directions without obvious systematic character.

4 Discussion

4.1 Sensitivity to progressive drying

We looked at the effects of the continuous progression of drying on the different catchments and found that, in general, even modest drying led to a continuous reduction of streamflow, soil moisture and groundwater storage on the one hand and on the other hand the moderate scenario already revealed catchments that were more sensitive to droughts than others. With the more extreme scenario the picture became even clearer. However, for the drought characteristic duration of days ~~above the~~ exceeding Q_{90}~~threshold, an effect was only visible after applying~~, only the more extreme scenario showed a clear effect. The driest year of the moderate scenario showed seasons with lower than the long-term mean streamflow values, that differed for catchments with different streamflow regimes. ~~As soon as the snow component needed to be considered, instead of~~ The lower elevation catchments had a long dry summer and fall~~,~~. In the higher elevation catchments there were again higher streamflow values ~~visible~~ in late summer~~. This~~, which could be explained by a filling of the storages in spring~~with snow melt water , that kept the storages at a higher level than~~. Snow melt water could fill the storages more than it would be possible if only rainfed (at least in the temperate humid climate of Switzerland). ~~Further~~ Other differences between the catchments with nival regimes have then to be accounted for by different storage release characteristics. This could be confirmed by the analysis of the historical drought in the summer of 2003 compared to a scenario with drier initial conditions ~~since~~ as the storages for the different catchments contributed in different proportions to the reduced streamflow under drier initial conditions.

The relative differences were small, but the initial conditions can have noticeable impacts even when looking at a whole year. The differences due to initial conditions varied between about 50% and 80%, which is in the same order of magnitude as what might be expected due to climate change (e.g., Lettenmaier et al., 1999; Nijssen et al., 2001) .

Comparing the drought sensitivities to catchment characteristics revealed that for both streamflow (I_{rel}) as well as duration of days above the Q_{90} threshold mean catchment elevation, size and slope were the main controls. Kroll et al. (2004), who tested different catchment characteristics as to their suitability to improve the regionalization of low flows in the US, found that signatures describing hydrogeology, slope and size and also elevation were important and improved low-flow regional regression models. However, while size was an important predictor for almost every region they investigated, elevation improved low flow prediction only in a few regions of the US. For soil moisture storage only size and slope control drought sensitivity and for groundwater storage only elevation and slope control drought sensitivity. ~~This means that the variability of the storages is not controlled by the same catchment characteristics as the resulting streamflow. However, streamflow as it integrates the catchment processes,~~ Streamflow showed all the controls of the storages. The fact that mean catchment elevation is important for drought sensitivity in streamflow can be partly explained by snow in higher elevations. ~~Other reasons like greater storages~~ The investigation of the direct role of snow showed that only for some indicators the sensitivity is snow dependent. For some sensitivity indicators particular looking at drought characteristics did not change with a no-snow-simulation. Snow is influencing sensitivities but cannot explain all difference between the catchments. Other explanations for the sensitivity differences with elevation such as larger groundwater storage in higher elevation catchments are indicated by the relationship between groundwater storage and mean catchment elevation.

~~The catchment characteristic hydrogeology~~ Hydrogeology could be expected to be correlated to a storage dependent drought sensitivity (Stahl and Demuth, 1999; Kroll et al., 2004), however we could not find ~~any relationship . It could be that the hydrogeological productivity number was not an appropriate measure for storage and release~~a clear relationship using hydrogeological productivity with assigned numerical values. It could ~~also~~ be that the other controls dominated and hence secondary effects like geology or land-use, which are also very diverse and show a high variability among the catchments, did not show any correlation. ~~The~~ It also could be that the hydrogeological productivity number was not an appropriate measure for storage and release. The additional test to calibrate the numbers assigned to each productivity class in order to find the highest correlation between drought sensitivity measures and the hydrogeological productivity number yielded a significant correlation between hydrogeology and storage dependent drought sensitivity. Hence, even with the coarse hydrogeological information on which the hydrogeological productivity number was based it is possible to establish a relationship between drought sensitivity and hydrogeology. The improvement with the calibration and the resulting values for the productivity classes are to some degree dependent on the studied catchments. It would be good in a next step to test this dependency with a larger group of catchments. This is an important task, as the information about hydrogeological productivity could help to better estimate the sensitivity of specific catchments to droughts.

4.2 Model uncertainties

The results that are derived from the modeling experiment contain potential sources of uncertainty, i.e. mainly the choice of ~~the~~ these hydrological model and its associated structure and parametrization. The uncertainty from the model parametrization was addressed by an ensemble approach, which generated a more robust simulation than would have been the case for single “best” parametrization. Concerning the model structure we can assume that the main indication of the results of the streamflow simulation should be similar for different conceptual hydrological models, whereas we can expect some differences in the simulated storages.

~~Clearly it must be stated that the scenarios that~~

4.3 Construction of the scenarios

The simulations from the scenarios clearly depended on the inter-annual variability of precipitation for each catchment. Hence, we removed the effect of precipitation variability in the analysis by dividing the IQR values by the inter-quartile range of the precipitation ratio. Following many studies that document the sensitivity of streamflow to climate and climate change, Schaake et al. (1990) , Dooge (1992) , and Sankarasubramanian et al. (2001) introduced and applied the so called streamflow elasticity, which describes the sensitivity of streamflow to precipitation. The streamflow elasticity was developed as a robust, unbiased approach that on average and over many applications might discern the true sensitivity of streamflow to climate (Sankarasubramanian et al., 2001) . Similar to our approach, the streamflow elasticity is calculated by taking annual streamflow and precipitation into account (Sawicz et al., 2011) . In our approach we ensured that the inter-annual variability of the weather of a catchment would not overprint other catchment properties.

The scenarios were constructed by applying sorted annual or monthly precipitation, while air temperature was not considered explicitly. Null et al. (2010) considered air temperature and analyzed streamflow and particular low flow sensitivities to climate change by using scenarios with increased temperatures, but constant precipitation for mountain catchments. However, the results of previous case studies considering total streamflow response to changes in precipitation and temperature indicated that future total streamflow is more sensitive to precipitation than to temperature (Lettenmaier et al., 1999; Nijssen et al., 2001) .

The initial wetness was not considered for the construction of the scenarios but only the annual sums of precipitation, i.e. there might have been a dry year with a wet end of the year. This could lead to actual drier or wetter initial conditions for the following year than expected from the annual sum, particularly for the SoYe scenario. We minimized this effect by using hydrological years starting on October 1. Still, there could have been a dry summer in an otherwise relatively wet year which then serves as initial conditions for the following year. However the effect should be low compared to a start in winter with, for instance, a large snow cover at the end of an otherwise dry year.

The scenarios that were used did not aim to be realistic~~. For instance, the~~ , but should rather give an indication about a general sensitivity to drought. The precipitation in the scenarios decreased intentionally over the course of the years, which causes unnatural autocorrelations. Other studies that use, e.g., GCM output extreme climate change scenarios for climate impact studies, keep the natural variation of precipitation from year to year (e.g., Miller et al., 2003; Burke et al., 2006). ~~Instead~~ In our scenarios potential feedback mechanisms were not considered. A sustained reduction in precipitation would impact potential evaporation and air temperature (e.g., Trenberth et al., 2014) and over the course of decades there also a shift in vegetation to vegetation adapted to dry conditions could be expected (e.g., Bréda et al., 2006) . Instead, the scenarios in this study were constructed to get an idea of how strongly a catchment would react to a moderate and to an extreme progression of drying in comparison with a sample of other catchments from the temperate humid climate of Switzerland. The scenarios ~~were also derived in order~~ help to better understand how strongly initial conditions affect hydrological droughts, and were appropriately constructed for this purpose.

As a next step it would be interesting to perform an analysis similar to the one in this study for other regions as well as to find a system of general drivers that make a specific catchments vulnerable to droughts or not. A ranking for the different catchments that could help drought managers as a starting point to decide on which catchments are more vulnerable to droughts can easily be derived from our results. In addition to the scenarios used in this study, there is also the possibility to construct scenarios that have time fractions for sorting that are in between the yearly and the monthly construction of this study, for example, scenarios using half a year, a quarter of a year or two months.

5 Conclusions

This study demonstrates that hypothetical scenarios can be used to evaluate the sensitivity of catchments to droughts. The ~~reaction~~ response of streamflow as well as soil moisture and groundwater storages to a continuous progression of drying was analyzed both in general as well as focused on drought characteristics and on one historical drought event. Our analysis showed that mean catchment elevation, size and slope were the main controls on the sensitivity of the catchments to drought. The results suggest that higher elevation catchments with steeper slopes were less sensitive to droughts than lower elevation catchments with less steep slopes. The soil moisture storage was significantly correlated to catchment size, where we found smaller catchments to be less sensitive to droughts than larger catchments. We did not find a clear ~~connection~~ relationship between drought sensitivity and hydrogeology, however another choice of the productivity classes would lead to such a relationship. Generally, for water resource management it is important to look at both streamflow sensitivity and storage sensitivity to droughts. With our model-based approach the sensitivity of both can be easily estimated. This approach can serve as a starting point for water resources managers to understand the vulnerability of their catchments.

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Table 1. Catchment characteristics (FOEN, 2013b) and calibration results; the catchments are sorted by mean catchment elevation. F_{LS} is the model efficiency (Eq. 1).

Number	River	Area	Mean elevation	Regime type	Productivity[a]	Fores
		[~~km^2~~km^2]	[~~$m.a.s.l.$~~m. a.s.l.]	[-]	[-]	[%
1	Aach	48.5	480	pluvial	~~0.35~~0.27	0.33
2	Ergolz	261	590	pluvial	0.37	0.41
3	Aa	55.6	638	pluvial	0.24	0.22
4	Murg	78.9	650	pluvial	0.28	~~0.31~~0.27
5	Mentue	105	679	pluvial	0.15	~~0.28~~0.16
6	Broye	392	710	pluvial	0.23	~~0.25~~0.23
7	Langeten	59.9	766	pluvial	~~0.35~~0.36	0.19
8	Rietholz	3.3	795	pluvial	0.25	0.21
9	~~Goldach49.8833pluvial0.110.310.82-0.8310~~Guerbe	117	873	pluvial	~~0.30~~0.33	0.33
~~11~~10	Biber	31.9	1009	pluvial	~~0.22~~0.23	0.41
~~12~~11	Kleine Emme	477	1050	nivo-pluvial	0.21	0.35
~~13~~12	Ilfis	188	1051	nivo-pluvial	0.24	0.46
~~14~~13	Sense	352	1068	pluvio-nival	~~0.23~~0.24	0.33
~~15~~14	Alp	46.6	1155	nivo-pluvial	~~0.22~~0.23	0.45
~~16~~15	Emme	124	1189	nival	0.17	0.32
~~17~~16	Sitter	261	1252	nival	~~0.31~~0.08	0.22
~~18~~17	Erlenbach	0.64	1300	nivo-pluvial	~~0.05~~0.10	0.60
~~19~~18	Luempenen	0.93	1318	nivo-pluvial	~~0.50~~0.31	0.35
~~20~~19	Grande Eau	132	1560	nival	~~0.20~~0.21	0.33
~~21~~20	Schaechen	109	1717	nival	~~0.28~~0.29	0.16
~~22~~21	Allenbach	28.8	1856	nivo-glaciaire	~~0.12~~0.10	0.13
~~23~~22	Riale di Calneggia	24	1996	nivo-pluvial	0.26	0.07
23	Ova da Cluozza	26.9	2368	nival	0.47	0.05
24	Dischma	43.3	2372	glacio-nival	~~0.25~~0.21	0.02

[a] Values of area-weighted catchment average assigned to hydrogeological productivity classes: not=0; little=0.25;variable=0.5;productive=1

Table 2. Spearman rank correlation coefficients between the catchment characteristics from Table 1. All correlations were significant at the 5% level.

	Elevation	Size	Slope	Prod. no.	Forest
Elevation	1.000	-0.362	0.853	-0.130	-0.328
Size		1.000	-0.563	-0.131	0.236
Slope			1.000	0.012	-0.108
Prod. no.				1.000	-0.244
Forest					1.000

Table 3. Drought indicators for all catchments. ~~Note that for all indicators the~~ The smaller the value the less sensitive the catchment is to drying~~, and the smaller the values of $\Delta Q_{driestSoYe}$ and $\Delta Q_{driestSoMo}$, the more sensitive the catchment is to drying~~.

Catchment	$I_{relQsim}$	I_{relSM}	I_{relGW}	IQR_{Q90}	ΔQ_{2003}	ΔSM_{2003}	ΔGW_{2003}	$\Delta Q_{driestSoYe}$	ΔQ_{driest}
Aach	1.701	0.436	1.499	0.154	0.024	~~0.510~~ 0.511	0.025	~~0.586~~ 0.719	~~0.022~~ 1
Ergolz	1.802	0.471	1.588	0.236	0.026	~~0.314~~ 0.315	0.037	~~0.526~~ 0.737	~~0.020~~ 1
Aa	1.653	0.493	1.338	0.199	0.015	0.364	~~0.121~~ 0.120	~~0.745~~ 0.848	~~0.026~~ 1
Murg	1.558	0.462	1.507	0.207	0.028	~~0.496~~ 0.497	0.031	~~0.634~~ 1.383	~~0.032~~ 1
Mentue	1.772	0.521	1.487	0.373	~~0.037~~ 0.038	~~0.351~~ 0.354	~~0.046~~ 0.047	~~0.353~~ 0.972	~~0.014~~ 1
Broye	1.675	0.485	1.360	0.386	0.021	~~0.492~~ 0.495	0.036	~~0.365~~ 1.362	~~0.019~~ 1
Langeten	1.706	0.515	1.503	0.803	~~0.057~~ 0.058	~~0.449~~ 0.451	~~0.069~~ 0.071	~~0.532~~ 1.290	~~0.056~~ 1
Rietholz	1.668	0.198	1.483	0.207	0.001	0.281	0.001	~~0.596~~ 1.934	~~0.003~~ 2
Guerbe	1.644	0.488	1.369	0.309	~~0.022~~ 0.025	~~0.440~~ 0.444	~~0.028~~ 0.031	~~0.604~~ 1.419	~~0.053~~ 1
Biber	1.516	0.347	1.077	0.143	0.009	0.348	0.018	~~0.778~~ 2.257	~~0.038~~ 2
Kleine Emme	1.477	0.397	0.245	0.178	~~0.045~~ 0.049	~~0.465~~ 0.469	~~0.943~~ 0.919	~~0.617~~ 2.195	~~0.086~~ 2
Ilfis	1.695	0.446	1.465	0.240	~~0.193~~ 0.198	~~0.582~~ 0.583	~~0.276~~ 0.283	~~0.568~~ 1.915	~~0.059~~ 2
Sense	1.572	0.498	1.328	0.208	~~0.026~~ 0.027	~~0.473~~ 0.478	~~0.043~~ 0.046	~~0.565~~ 1.619	~~0.056~~ 2
Alp	1.350	0.213	0.861	0.117	0.004	~~0.288~~ 0.290	~~0.009~~ 0.010	~~0.744~~ 3.544	~~0.055~~ 4
Emme	1.561	0.357	1.133	0.113	~~0.272~~ 0.325	~~0.716~~ 0.728	~~0.377~~ 0.432	~~0.643~~ 2.439	~~0.057~~ 3
Sitter	1.706	0.608	1.392	0.154	~~0.161~~ 0.173	~~0.477~~ 0.489	~~0.219~~ 0.230	~~0.628~~ 0.499	~~0.048~~ 1
Erlenbach	1.303	0.211	0.476	0.099	~~0.006~~ 0.007	~~0.303~~ 0.313	~~0.294~~ 0.314	~~0.744~~ 4.483	~~0.069~~ 5
Luempenen	1.346	0.280	0.467	0.155	~~0.017~~ 0.019	~~0.423~~ 0.428	~~0.361~~ 0.374	~~0.768~~ 4.665	~~0.067~~ 5
Grande Eau	1.522	0.457	0.626	0.376	~~0.058~~ 0.104	~~0.431~~ 0.459	~~0.687~~ 0.746	~~0.514~~ 2.609	~~0.136~~ 2
Schaechen	1.417	0.382	1.181	0.146	~~0.004~~ 0.008	~~0.331~~ 0.364	~~0.006~~ 0.010	~~0.704~~ 3.108	~~0.118~~ 3
Allenbach	1.480	0.334	1.350	0.105	~~0.007~~ 0.019	~~0.420~~ 0.477	~~0.008~~ 0.019	~~0.632~~ 3.053	~~0.068~~ 3
Riale di Calneggia	1.279	0.275	1.005	0.193	~~0.005~~ 0.008	~~0.382~~ 0.416	~~0.011~~ 0.020	~~0.567~~ 4.636	~~0.012~~ 5
Ova da Cluozza	1.468	0.587	1.267	0.256	~~0.048~~ 0.102	~~0.139~~ 0.168	~~0.091~~ 0.179	~~0.465~~ 1.797	~~0.019~~ 2
Dischma	1.270	0.370	1.196	0.105	~~0.008~~ 0.015	~~0.055~~ 0.067	~~0.008~~ 0.016	~~0.804~~ 2.187	~~0.110~~ 2

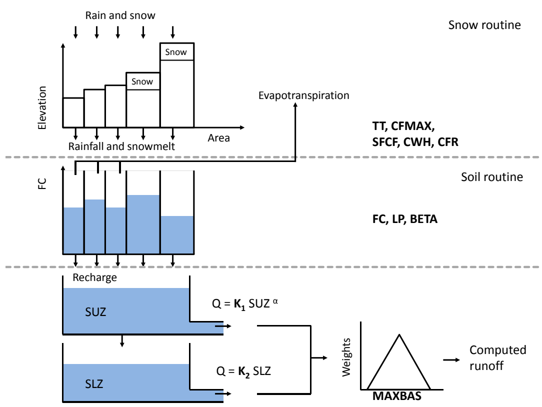

Fig. 1. Structure of the HBV model.

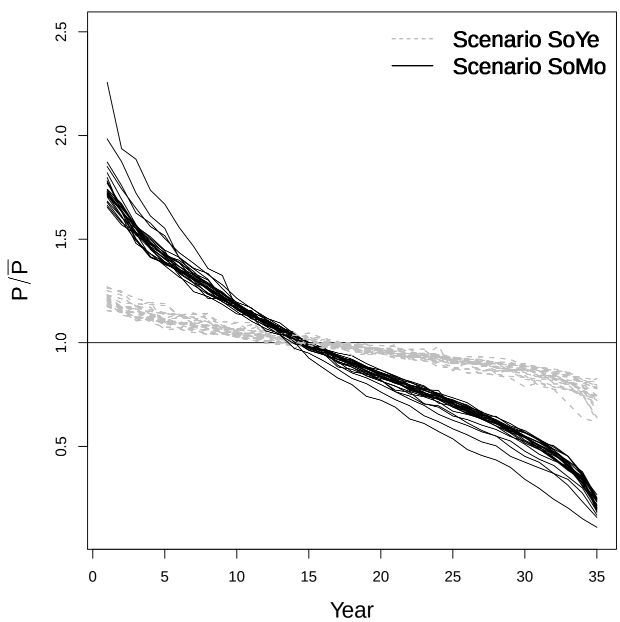

Fig. 2. Precipitation ratios of the annual precipitations P and the ~~longterm~~ long-term mean precipitation $\bar{P}$ for scenario SoYe and SoMo.

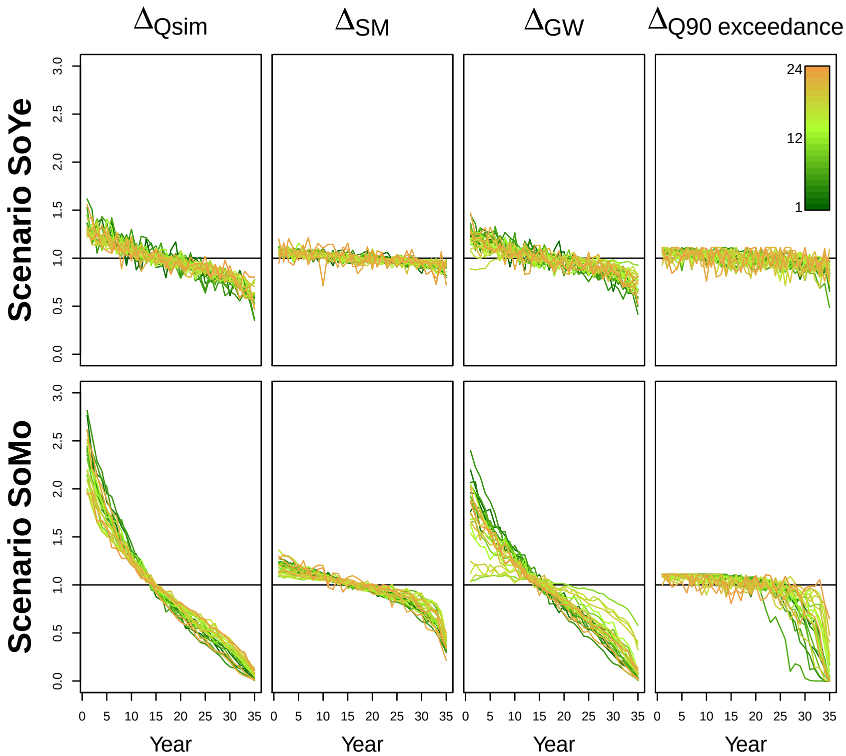

Fig. 3. Relative change of Q_{sim}, SM and GW and the Q_{90} exceedance days for the two scenarios to the ~~longterm~~ long-term reference for all catchments. Each color stands for one catchment number (Table 1), where the greener colors indicate catchments at lower mean elevation and the more brownish colors were used for catchments at higher mean elevation. Note, that the upper boundary of the relative change of Q_{90} is given by the fixed days that are exceeding Q_{90} per year and the maximum days per year.

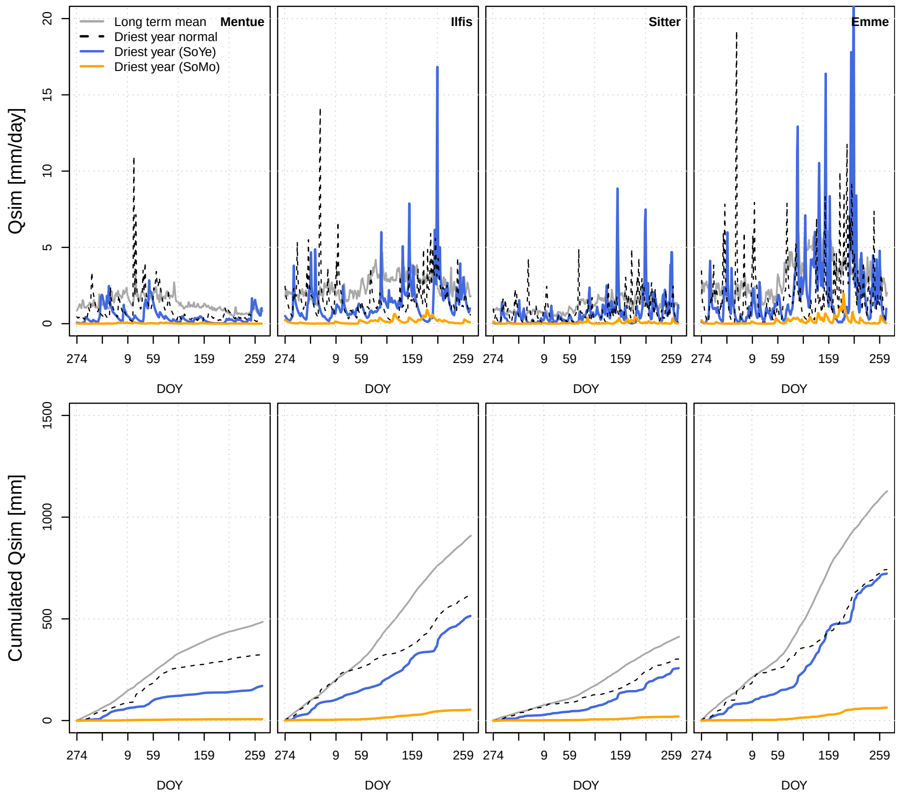

Fig. 4. Q_{sim} and cumulated Q_{sim} for long-term mean, driest year of the reference simulation as well as the driest years of the two scenarios for four example catchments.

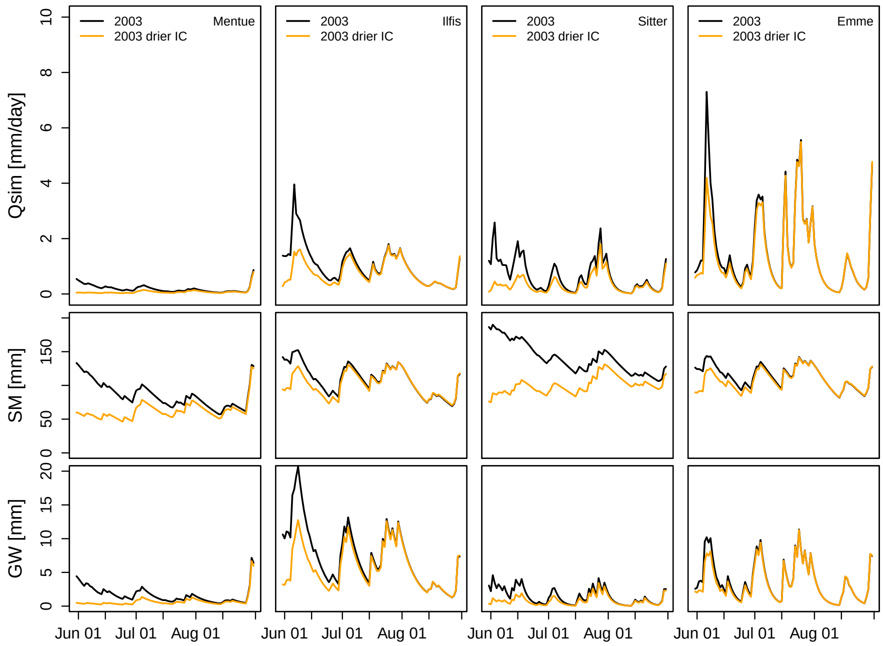

Fig. 5. Simulation (median of 100 simulations) of the summer drought 2003, original and with drier initial conditions (IC).

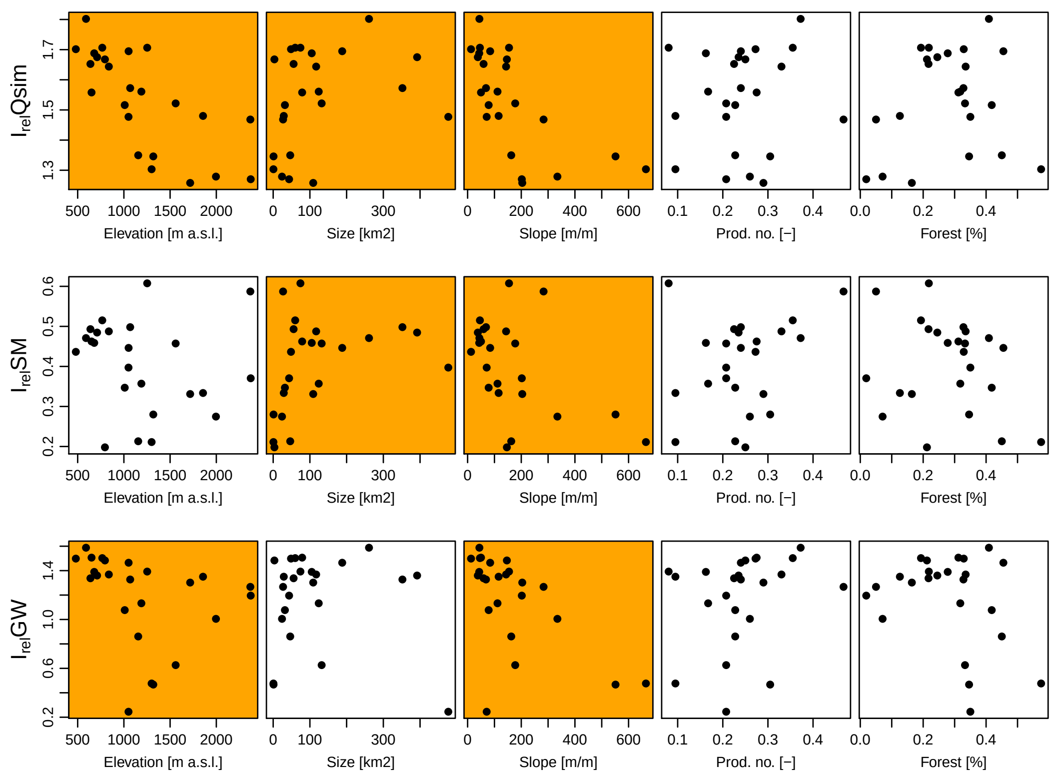

Fig. 6. I_{rel} for Q_{sim}, SM, and GW compared to simple catchment characteristics. The orange background indicates a significant correlation (5% level) between the respective I_{rel} and catchment characteristic. Prod.no. is the hydrogeological productivity number as introduced in 2.1

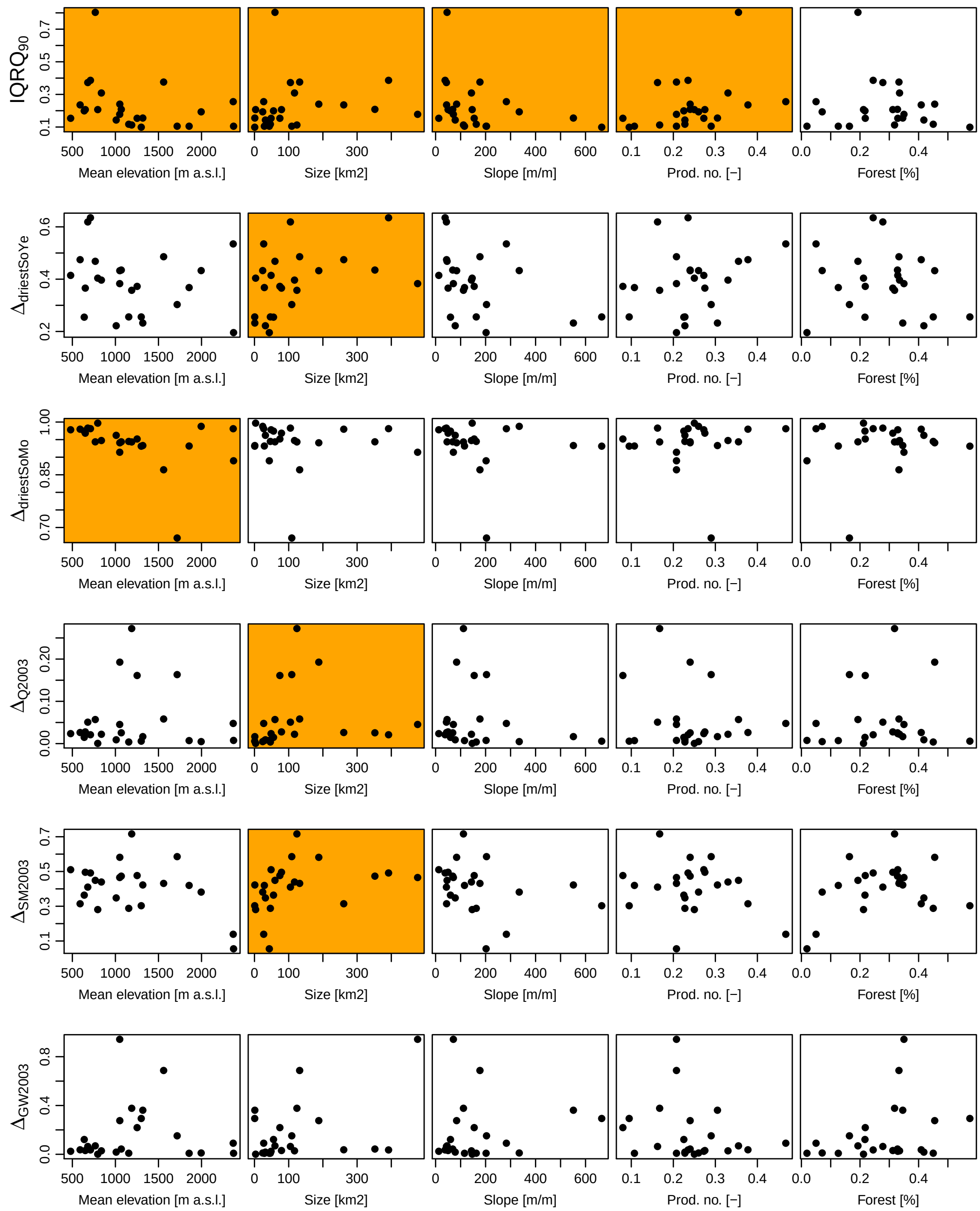

Fig. 7. Indicators to drought sensitivity: days above the threshold Q_{90}, $\Delta Q_{DriestSoYe}$, $\Delta Q_{DriestSoMo}$, and changes of summer 2003 with drier initial conditions ΔQ_{2003}, ΔSM_{2003} and ΔGW_{2003} compared to simple catchment characteristics. The orange background indicates a significant correlation (5% level) between the respective indicator and catchment characteristic. Prod.no. is the hydrogeological productivity number as introduced in 2.1

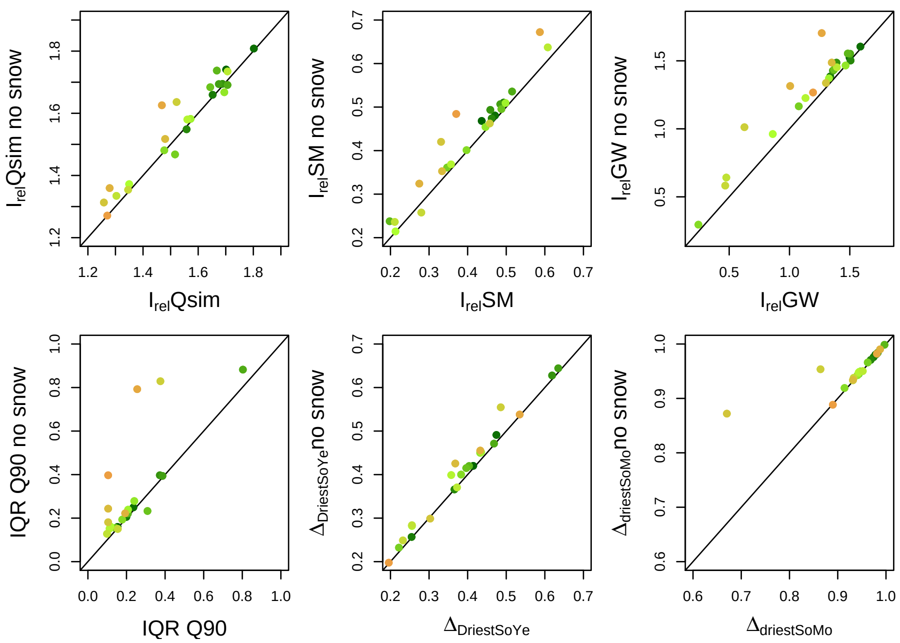

Fig. 8. Comparison of the different measures for the sensitivity to drying resulting from simulations in the natural settings and simulations without snow accumulation. The greener colors indicate catchments at (originally) lower mean elevation and the more brownish colors were used for catchments at (originally) higher mean elevation.