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Quantifying sensitivity to droughts – an experimental modeling approach

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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 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 intra-annual seasonality for the region. The sensitivity of 24 Swiss catchments to these scenarios was evaluated by analyzing the simulated discharge time series and modeled storages. Mean catchment elevation, slope and size were found to be the main controls on the sensitivity of catchment discharge to precipitation. Generally, catchments at higher elevation and with steeper slopes seemed to be 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 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 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, 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; Van Loon and Van Lanen, 2012): several consecutive meteorological droughts can turn into a combined and prolonged hydrological drought and they can be attenuated by the storages of a catchment. Further there is often a varying time lag between meteorological, soil moisture and hydrological drought that involves 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). 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 drought generating mechanisms, Van Loon et al. (2010) 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). 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 persistent occurrence of specific circulation patterns, however no clear link between temporal streamflow drought development and 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). 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 to investigate the different reactions of catchments to droughts.

In this study we address 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 drier meteorological conditions, based on observations.

2 Methods and data

2.1 Data

We selected 24 Swiss catchments, which vary in size, mean catchment elevation, land cover and geology (Table 1). To investigate the main natural underlying processes, 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 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, 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 assigned a numeric value to each of these productivity classes and computed an area-weighted mean.

2.2 HBV modeling experiment

For the modeling experiment we used the semi-distributed conceptual HBV model (Bergström , 1995; Lindström et al., 1997) with the version HBV light (Seibert and Vis, 2012). In this study the catchments were separated into elevation zones of 100 m. The model uses different routines (Fig. 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 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 , 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) and Lindström (1997). F_{LS} ranges between minus infinity for poor fits and 1 for a perfect fit,

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

One simulation was run for each of the parameter sets over the entire meteorological observation period and 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 for the scenarios.

2.3 Scenario construction

Two precipitation time series were constructed as 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.
- 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 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.

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, $\overline{x}$.

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

where x stands for the variable of interest, and i the year. Δx was calculated for simulated runoff (Q_{sim}), simulated soil moisture storage (SM), and the combined simulated upper and lower groundwater storages ($\text{GW} = \text{SUZ} + \text{SLZ}$) (Fig. 1) (Eq. 2). Secondly, to assess the catchment sensitivity to the progression of drying we calculated the inter-quartile range (IQR) of Δx.IQR represents the variability during the drying phase and 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 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 IQR was divided by the inter-quartile range of these precipitation ratios (Eq. 3). The so modified IQR is referred to as I_{rel}.

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

where Δx_{75} is the 75th percentile of Δx and Δx_{25} the 25th percentile of Δx. Even though this I_{rel} includes both wet and dry years, it gives an overall impression of the reaction of a catchment to the progression of drying. We also compared the extreme 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 drought characteristics more specifically, we counted the days per year that exceeded the 90th streamflow percentile (Q_{90}) of the respective reference simulation. 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 Q_{90} as x. Other indices describing the influence of the progression of drying at its extreme dry end, are the ratios of the mean of the driest year of each scenario and the long-term mean ($\Delta Q_{\mathrm{Driest\ SoYe}}$ for scenario SoYe; $\Delta Q_{\mathrm{Driest\ SoMo}}$ for scenario SoMo). The smaller these indices 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 scenario SoMo. Here, 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 catchment would have been affected if the preceding months to the 2003 drought event would have been drier than in the actual observation. 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 Q_{sim}, ΔSM_{2003} for SM, and ΔGW_{2003} for GW. The smaller these indices are, the less sensitive the respective catchments are to droughts.

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 (Fig. 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 $\Delta_{Q_{\text{sim}}}$ values were found for values greater than one (wetter conditions than the longterm mean) compared to lower elevation catchments. During drier conditions than the long-term mean, the $\Delta_{Q_{\text{sim}}}$ values of the catchments with higher elevations were smaller 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) relative to the longterm GW mean shows more variability between the catchments than for $\Delta_{Q_{\text{sim}}}$ (Fig. 3).

The general behavior was shown using four catchments as examples comparing the long-term mean and the driest year of the reference simulation (Fig. 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 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 variation between the catchments and thus their sensitivity to the continuous drying (Fig. 4). The difference between the last year SoYe and the driest year of the reference simulation resulted from the different initial conditions given by the preceding summer and was very small. The driest year of scenario SoMo resulted always in streamflow values below the long-term mean as well as below the driest year of the reference simulation and of the SoYe scenario for all catchments. For the pluvial Mentue catchment discharge nearly diminished for the driest year of the scenario. For the catchments with some snow influence there are 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. For the scenario SoMo, the cumulative sums show that the annual difference between long-term mean and the scenario varies for 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 for the SoYe scenario (Fig. 3). Even though over the course of the years a slight decrease of days exceeding the threshold could be noticed, there were still years at the end of the scenario that had longer durations of 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. For the SoMo scenario, however, there is a strong decrease in days exceeding the Q_{90} threshold with the progression of drying. In this scenario a difference between the catchments also became apparent: in the relatively wetter years, the lower elevation catchments already start 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 less days above the threshold compared to the long-term mean. The highest elevation catchments follow 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 SoMo, the highest elevation catchments show a clear decrease in days above the Q_{90} threshold at the dry end of the scenario.

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 (Fig. 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.

3.3 Importance of catchment characteristics

The comparison of the I_{rel} values, as a measure of sensitivity to droughts, with simple catchment characteristics showed, for Q_{sim}, significant correlation between the I_{rel} values and catchment mean elevation, size and slope, respectively (Fig. 6). Mean catchment elevation and drought sensitivity were correlated with higher mean catchment elevations 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 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 had no significant influence on the sensitivity of the catchments studied to droughts.

A summary of all indices can be found in Table 2. The drought targeting indices (IQR of days above the threshold Q_{90}, $\Delta Q_{\text{Driest SoYe}}$, $\Delta Q_{\text{Driest SoMo}}$, and changes of summer 2003 with drier initial conditions ΔQ_{2003}, ΔSM_{2003} and ΔGW_{2003}) could also be related to the catchment characteristics (Fig. 7); most of them were correlated with size, elevation or slope of the catchment: IQR of days above the threshold, 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 $\Delta Q_{\text{Driest SoYe}}$ and $\Delta Q_{\text{Driest SoMo}}$ 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 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).

Another 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 1 October, 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.

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 Q_{90} threshold, an effect was only visible after applying the more extreme scenario. 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 a long dry summer and fall, there were again higher streamflow values visible in late summer. This could be explained by a filling of the storages in spring with snow melt water, that kept the storages at a higher level than would be possible if only rainfed (at least in the temperate

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humid climate of Switzerland). Further 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 the storages for the different catchments contributed in different proportions to the reduced streamflow under drier initial conditions.

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. 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, 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 in higher elevation catchments are indicated by the relationship between groundwater storage and mean catchment elevation.

The catchment characteristic 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. It could also be that the other controls dominated and hence secondary effects like geology or landuse, which are also very diverse and show a high variability among the catchments, did not show any correlation.

The results that are derived from the modeling experiment contain potential sources of uncertainty, i.e. mainly the choice of the 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 were used did not aim to be realistic. For instance, 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 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 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 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 between drought sensitivity and hydrogeology. 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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References

Bergström, S.: The HBV model, edited by Singh, V.P., in: Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO., 443–476, 1995. 7664

Burke, E. J., Brown, S. J., and Christidis, N.: Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model, J. Hydrometeorol., 7, 1113–1125, 2006. 7674

Dooge, J. C.: Sensitivity of runoff to climate change: a Hortonian approach, B. Am. Meteorol. Soc., 73, 2013–2024, 1992. 7671

Eltahir, E. A. and Yeh, P. J.-F.: On the asymmetric response of aquifer water level to floods and droughts in Illinois, Water Resour. Res., 35, 1199–1217, 1999. 7661

Fleig, A. K., Tallaksen, L. M., Hisdal, H., and Demuth, S.: A global evaluation of streamflow drought characteristics, Hydrol. Earth Syst. Sci., 10, 535–552, doi:10.5194/hess-10-535-2006, 2006. 7662

FOEN: Federal Office for the Environment, section of hydrology, http://www.bafu.admin.ch/hydrologie/12385/index.html?lang=en (last access: 1 February 2013), 2013a. 7663

FOEN: Federal Office for the Environment, section of hydrology, http://www.hydrodaten.admin.ch/en/ (last access: 20 December 2013), 2013b. 7680

Frei, C.: Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances, Int. J. Climatol., 34, 1585–1605, 2013. 7663

Kohn, I., Rosin, K., Freudiger, D., Belz, J. U., Stahl, K., and Weiler, M.: Low flow in Germany in 2011, Hydrolog. Wasserwirt., 58, 4–17, 2014. 7661

Kroll, C., Luz, J., Allen, B., and Vogel, R. M.: Developing a watershed characteristics database to improve low streamflow prediction, J. Hydrol. Eng., 9, 116–125, 2004. 7673

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., and Kaspar, F.: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis, Climatic Change, 75, 273–299, 2006. 7662

Lettenmaier, D. P., Wood, A. W., Palmer, R. N., Wood, E. F., and Stakhiv, E. Z.: Water resources implications of global warming: a US regional perspective, Climatic Change, 43, 537–579, 1999. 7672

Li, J., Cook, E., Chen, F., Gou, X., D'Arrigo, R., and Yuan, Y.: An extreme drought event in the central Tien Shan area in the year 1945, J. Arid Environ., 74, 1225–1231, 2010. 7661

Lindström, G.: A simple automatic calibration routine for the HBV model, Nord. Hydrol., 28, 153–168, 1997. 7665

Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergström, S.: Development and test of the distributed HBV-96 hydrological model, J. Hydrol., 201, 272–288, 1997. 7664, 7665

MeteoSwiss: Federal Office of Meteorology and Climatology, http://www.meteoschweiz.admin.ch/web/en/services/data_portal/gridded_datasets.html, last access: 10 October 2013. 7663

Miller, N. L., Bashford, K. E., and Strem, E.: Potential impacts of climate change on California hydrology, J. Am. Water Resour. As., 39, 771–784, 2003. 7674

Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 202–216, 2010. 7661

Nijssen, B., O'Donnell, G. M., Hamlet, A. F., and Lettenmaier, D. P.: Hydrologic sensitivity of global rivers to climate change, Climatic Change, 50, 143–175, 2001. 7672

Null, S. E., Viers, J. H., and Mount, J. F.: Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada, PLoS One, 5, e9932, doi::10.1371/journal.pone.0009932, 2010. 7672

Peters, E., Torfs, P., Van Lanen, H., and Bier, G.: Propagation of drought through groundwater – a new approach using linear reservoir theory, Hydrol. Process., 17, 3023–3040, 2003. 7661

Rebetez, M., Mayer, H., Dupont, O., Schindler, D., Gartner, K., Kropp, J. P., and Menzel, A.: Heat and drought 2003 in Europe: a climate synthesis, Ann. For. Sci., 63, 569–577, 2006. 7661

Sankarasubramanian, A., Vogel, R. M., and Limbrunner, J. F.: Climate elasticity of streamflow in the United States, Water Resour. Res., 37, 1771–1781, 2001. 7671

Santos, J., Corte-Real, J., and Leite, S.: Atmospheric large-scale dynamics during the 2004/2005 winter drought in Portugal, Int. J. Climatol., 27, 571–586, 2007. 7661

Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., and Carrillo, G.: Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA, Hydrol. Earth Syst. Sci., 15, 2895–2911, doi:10.5194/hess-15-2895-2011, 2011. 7671

Schaake, J. C.: From climate to flow, edited by Waggoner, P., in: Climate Change and US Water Resources, John Wiley, New York, 177–206, 1990. 7671

Seibert, J.: Regionalisation of parameters for a conceptual rainfall-runoff model, Agr. Forest Meteorol., 98, 279–293, 1999. 7664

Seibert, J.: Multi-criteria calibration of a conceptual runoff model using a genetic algorithm, Hydrol. Earth Syst. Sci., 4, 215–224, doi:10.5194/hess-4-215-2000, 2000. 7664

Seibert, J. and Vis, M. J. P.: Teaching hydrological modeling with a user-friendly catchment-runoff-model software package, Hydrol. Earth Syst. Sci., 16, 3315–3325, doi:10.5194/hess-16-3315-2012, 2012. 7664

Solomon, S.: Climate Change 2007 – The Physical Science Basis, Working Group I Contribution to the Fourth Assessment Report of the IPCC, vol. 4, Cambridge University Press, 2007. 7661

Spreafico, M., Leibundgut, C., and Weingartner, R.: Hydrologischer Atlas der Schweiz: Atlas hydrologique de la Suisse, Bundesamt für Landestopographie, Berne, Switzerland, 1992. 7663

Stahl, K. and Demuth, S.: Linking streamflow drought to the occurrence of atmospheric circulation patterns, Hydrolog. Sci. J., 44, 467–482, 1999. 7662, 7673

Tallaksen, L. M. and Van Lanen, H. A.: Hydrological Drought: Processes and Estimnation Methods for Streamflow and Groundwater, vol. 48, Elsevier, Amsterdam, 2004. 7661

Teutschbein, C. and Seibert, J.: Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods, J. Hydrol., 456, 12–29, 2012. 7662

Teutschbein, C. and Seibert, J.: Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions?, Hydrol. Earth Syst. Sci., 17, 5061–5077, doi:10.5194/hess-17-5061-2013, 2013. 7662

Trigo, R. M., Gouveia, C. M., and Barriopedro, D.: The intense 2007–2009 drought in the Fertile Crescent: impacts and associated atmospheric circulation, Agr. Forest Meteorol., 150, 1245–1257, 2010. 7661

Van Loon, A. F. and Van Lanen, H. A. J.: A process-based typology of hydrological drought, Hydrol. Earth Syst. Sci., 16, 1915–1946, doi:10.5194/hess-16-1915-2012, 2012. 7661

Van Loon, A. F., van Lanen, H. A., Hisdal, H., Tallaksen, L. M., Fendeková, M., Oosterwijk, J., Horvát, O., and Machlica, A.: Understanding hydrological winter drought in Europe, in: Global Change: Facing Risks and Threats to Water Resources, IAHS Publ., 340, 189–197, 2010. 7662

Wang, G.: Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment, Clim. Dynam., 25, 739–753, 2005. 7662

Wetherald, R. and Manabe, S.: Detectability of summer dryness caused by greenhouse warming, Climatic Change, 43, 495–511, 1999. 7662

Wetherald, R. T. and Manabe, S.: Simulation of hydrologic changes associated with global warming, J. Geophys. Res., 107, 4379, doi:10.1029/2001JD001195, 2002. 7662

Wilby, R. L. and Harris, I.: A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, UK, Water Resour. Res., 42, W02419, doi:10.1029/2005WR004065, 2006. 7662

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Zaidman, M. D., Rees, H. G., and Young, A. R.: Spatio-temporal development of streamflow droughts in north-west Europe, Hydrol. Earth Syst. Sci., 6, 733–751, doi:10.5194/hess-6-733-2002, 2002. 7662

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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 [km^2]	Mean elevation [m. a.s.l.]	Regime type [–]	Productivity* [–]	Forest [%]	Range F_{LS} [–]
1	Aach	48.5	480	pluvial	0.35	0.33	0.79–0.82
2	Ergolz	261	590	pluvial	0.37	0.41	0.84–0.86
3	Aa	55.6	638	pluvial	0.24	0.22	0.82–0.84
4	Murg	78.9	650	pluvial	0.28	0.31	0.81–0.83
5	Mentue	105	679	pluvial	0.15	0.28	0.79–0.82
6	Broye	392	710	pluvial	0.23	0.25	0.80–0.81
7	Langeten	59.9	766	pluvial	0.35	0.19	0.70–0.74
8	Rietholz	3.3	795	pluvial	0.25	0.21	0.72–0.74
9	Goldach	49.8	833	pluvial	0.11	0.31	0.82–0.83
10	Guerbe	117	873	pluvial	0.30	0.33	0.78–0.80
11	Biber	31.9	1009	pluvial	0.22	0.41	0.82–0.84
12	Kleine Emme	477	1050	nivo-pluvial	0.21	0.35	0.82–0.82
13	Ilfis	188	1051	nivo-pluvial	0.24	0.46	0.78–0.81
14	Sense	352	1068	pluvio-nival	0.23	0.33	0.77–0.79
15	Alp	46.6	1155	nivo-pluvial	0.22	0.45	0.76–0.78
16	Emme	124	1189	nival	0.17	0.32	0.74–0.78
17	Sitter	261	1252	nival	0.31	0.22	0.73–0.74
18	Erlenbach	0.64	1300	nivo-pluvial	0.05	0.60	0.75–0.77
19	Luempenen	0.93	1318	nivo-pluvial	0.50	0.35	0.76–0.77
20	Grande Eau	132	1560	nival	0.20	0.33	0.79–0.81
21	Schaechen	109	1717	nival	0.28	0.16	0.90–0.92
22	Allenbach	28.8	1856	nivo-glaciaire	0.12	0.13	0.73–0.76
23	Riale di Calneggia	24	1996	nivo-pluvial	0.26	0.07	0.80–0.82
24	Dischma	43.3	2372	glacio-nival	0.25	0.02	0.77–0.81

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

Table 2. Drought indicators for all catchments. Note that for all indicators the smaller the value the less sensitive the catchment is to drying, and the smaller the values of $\Delta Q_{\text{Driest SoYe}}$ and $\Delta Q_{\text{Driest SoMo}}$, the more sensitive the catchment is to drying.

Catchment	$I_{\text{rel } Q_{\text{sim}}}$	$I_{\text{rel SM}}$	$I_{\text{rel GW}}$	$\text{IQR}_{Q_{90}}$	ΔQ_{2003}	ΔSM_{2003}	ΔGW_{2003}	$\Delta Q_{\text{Driest SoYe}}$	$\Delta Q_{\text{Driest SoMo}}$
Aach	1.701	0.436	1.499	0.154	0.024	0.510	0.025	0.586	0.022
Ergolz	1.802	0.471	1.588	0.236	0.026	0.314	0.037	0.526	0.020
Aa	1.653	0.493	1.338	0.199	0.015	0.364	0.121	0.745	0.026
Murg	1.558	0.462	1.507	0.207	0.028	0.496	0.031	0.634	0.032
Mentue	1.772	0.521	1.487	0.373	0.037	0.351	0.046	0.353	0.014
Broye	1.675	0.485	1.360	0.386	0.021	0.492	0.036	0.365	0.019
Langeten	1.706	0.515	1.503	0.803	0.057	0.449	0.069	0.532	0.056
Rietholz	1.668	0.198	1.483	0.207	0.001	0.281	0.001	0.596	0.003
Guerbe	1.644	0.488	1.369	0.309	0.022	0.440	0.028	0.604	0.053
Biber	1.516	0.347	1.077	0.143	0.009	0.348	0.018	0.778	0.038
Kleine Emme	1.477	0.397	0.245	0.178	0.045	0.465	0.943	0.617	0.086
Ilfis	1.695	0.446	1.465	0.240	0.193	0.582	0.276	0.568	0.059
Sense	1.572	0.498	1.328	0.208	0.026	0.473	0.043	0.565	0.056
Alp	1.350	0.213	0.861	0.117	0.004	0.288	0.009	0.744	0.055
Emme	1.561	0.357	1.133	0.113	0.272	0.716	0.377	0.643	0.057
Sitter	1.706	0.608	1.392	0.154	0.161	0.477	0.219	0.628	0.048
Erlenbach	1.303	0.211	0.476	0.099	0.006	0.303	0.294	0.744	0.069
Luempenen	1.346	0.280	0.467	0.155	0.017	0.423	0.361	0.768	0.067
Grande Eau	1.522	0.457	0.626	0.376	0.058	0.431	0.687	0.514	0.136
Schaechen	1.417	0.382	1.181	0.146	0.004	0.331	0.006	0.704	0.118
Allenbach	1.480	0.334	1.350	0.105	0.007	0.420	0.008	0.632	0.068
Riale di Calneggia	1.279	0.275	1.005	0.193	0.005	0.382	0.011	0.567	0.012
Ova da Cluozza	1.468	0.587	1.267	0.256	0.048	0.139	0.091	0.465	0.019
Dischma	1.270	0.370	1.196	0.105	0.008	0.055	0.008	0.804	0.110

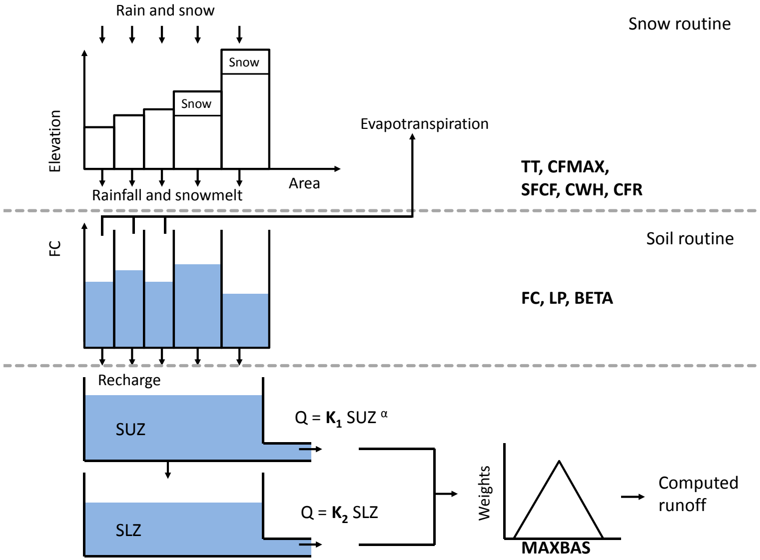

Figure 1. Structure of the HBV model.

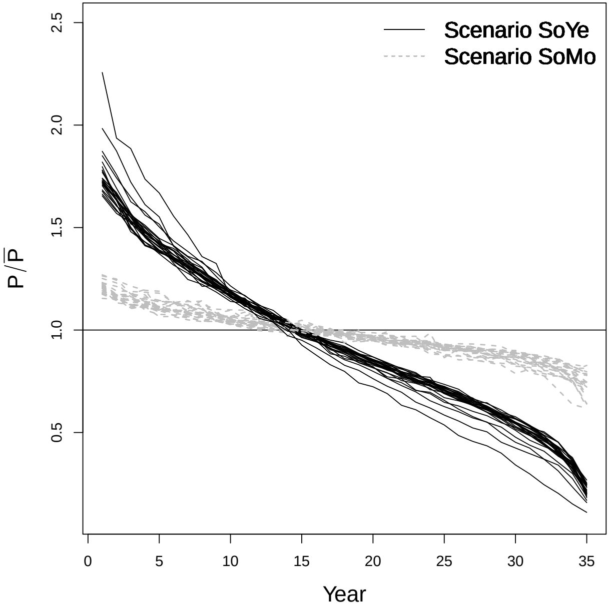

Figure 2. Precipitation ratios of the annual precipitations P and the longterm mean precipitation $\bar{P}$ for scenario SoYe and SoMo.

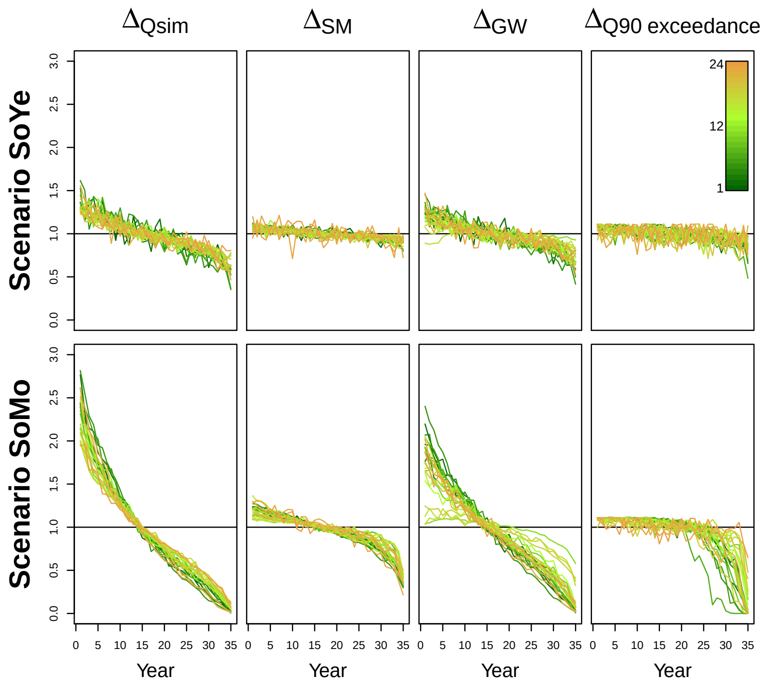

Figure 3. Relative change of Q_{sim}, SM and GW and the Q_{90} exceedance days for the two scenarios to the longterm reference for all catchments. Each color stands for one catchment number (Table 1), where the greener colors indicate catchments at lower mean elevation and the more brownish colors were used for catchments at higher mean elevation.

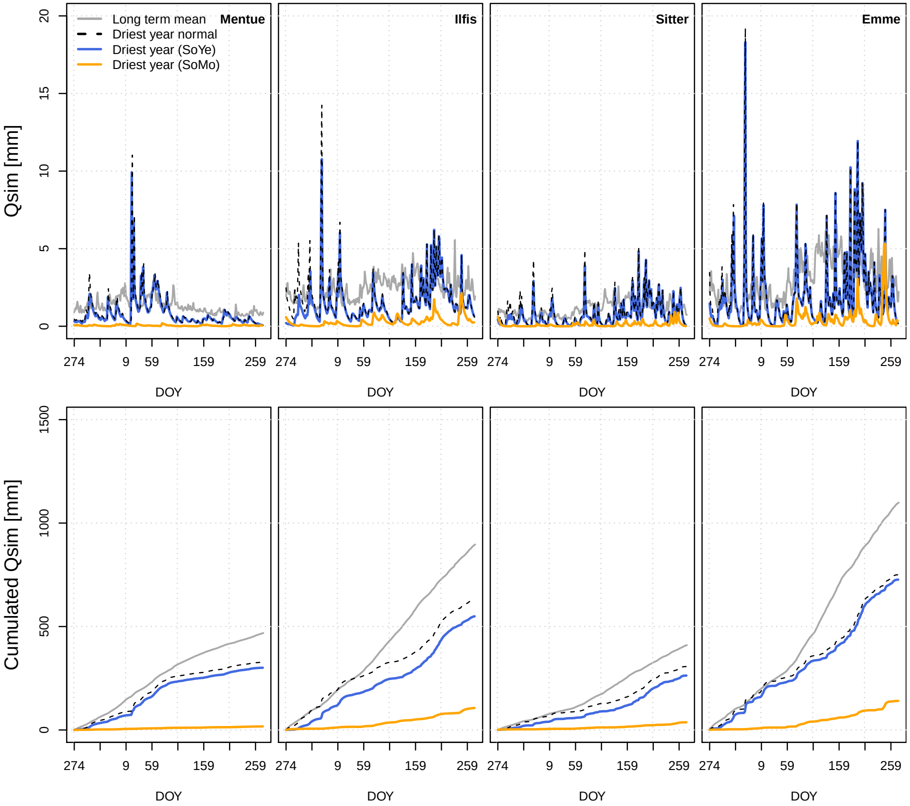

Figure 4. Q_{sim} and cumulated Q_{sim} for long-term mean, driest year of the reference simulation as well as the driest years of the two scenarios for four example catchments.

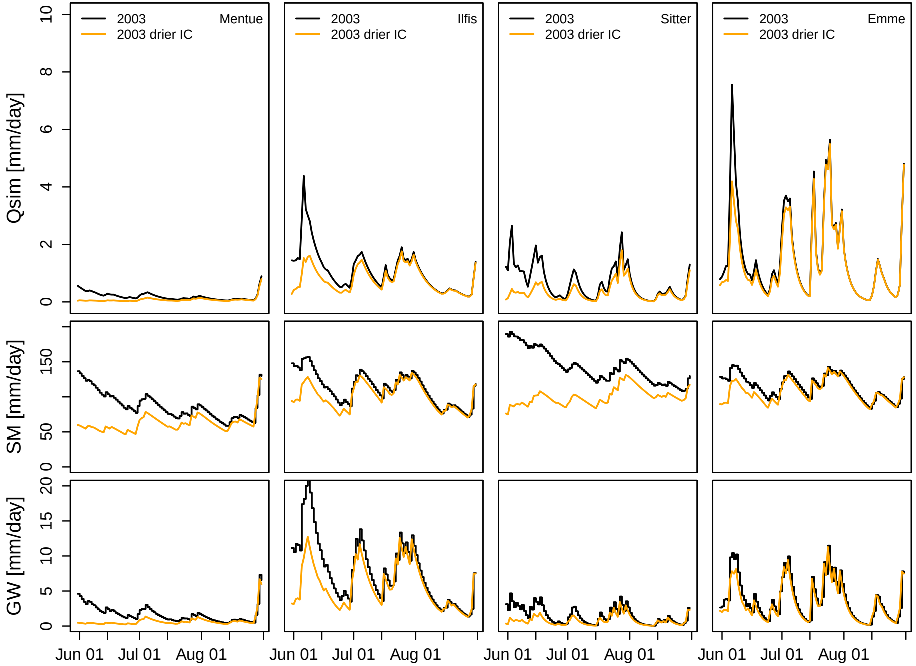

Figure 5. Simulation (median of 100 simulations) of the summer drought 2003, original and with drier initial conditions (IC).

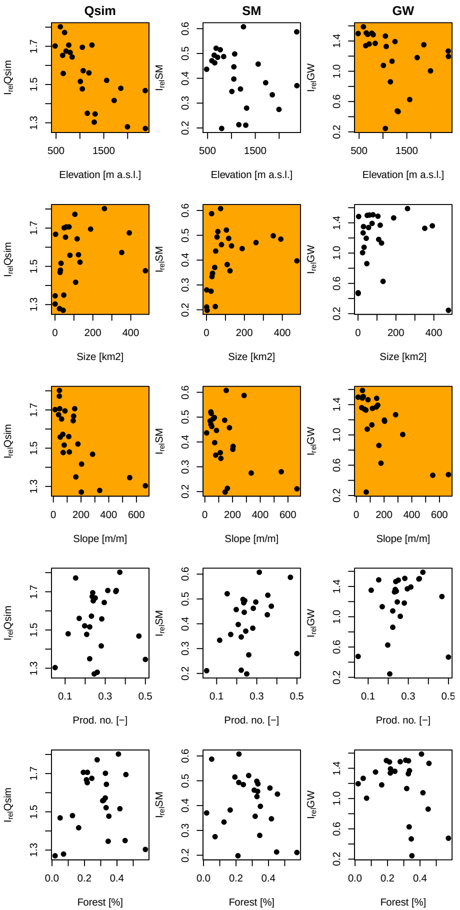

Figure 6. I_{rel} for Q_{sim}, SM, and GW compared to simple catchment characteristics. The orange background indicates a significant correlation (5 % level) between the respective I_{rel} and catchment characteristic.

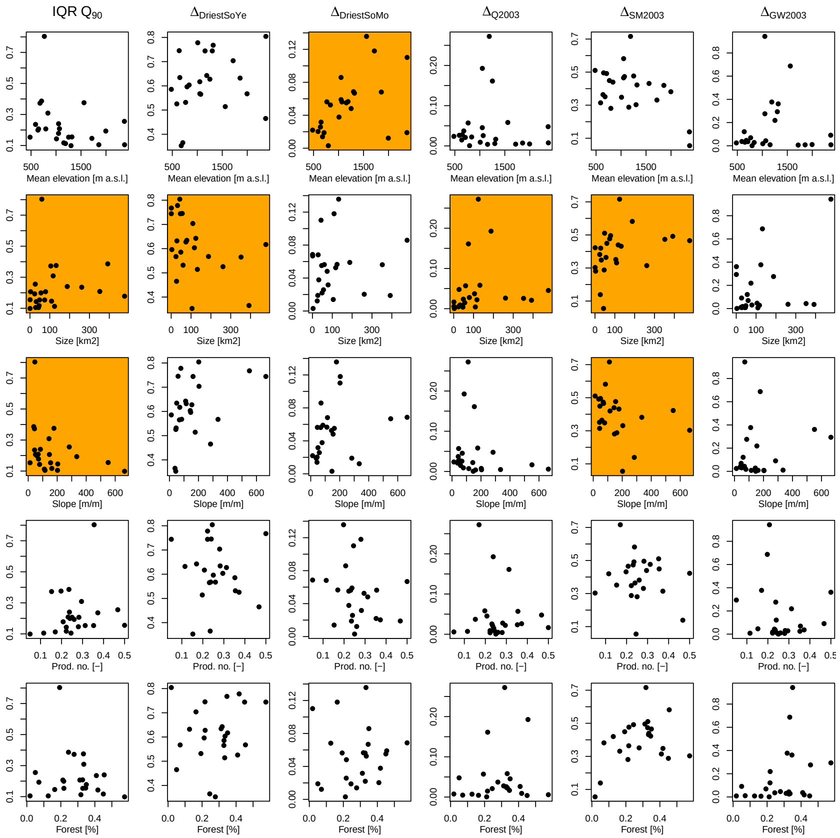

Figure 7. Indicators to drought sensitivity: days above the threshold Q_{90}, $\Delta Q_{\text{Driest SoYe}}$, $\Delta Q_{\text{Driest SoMo}}$, and changes of summer 2003 with drier initial conditions ΔQ_{2003}, ΔSM_{2003} and ΔGW_{2003} compared to simple catchment characteristics. The orange background indicates a significant correlation (5 % level) between the respective indicator and catchment characteristic.