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Predictability of low flow - an assessment with simulation experiments

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Abstract

Since the extreme summer of 2003 the importance of early drought warning has become increasingly recognized even in water-rich countries such as Switzerland. Spring 2011 illustrated drought conditions in Switzerland again, which are expected to become more frequent in the future. Two fundamental questions related to drought early warning are: 1) How long before a hydrological drought occurs can it be predicted? 2) How long are initial conditions important for streamflow simulations? To address these questions, we assessed the relative importance of the current hydrological state and weather during the prediction period. Ensemble streamflow prediction (ESP) and reverse ESP (ESP_{rev}) experiments were performed with the conceptual catchment model, HBV, for 21 Swiss catchments. The relative importance of the initial hydrological state and weather during the prediction period was evaluated by comparing the simulations of both experiments to a common reference simulation. To further distinguish between effects of weather and catchment properties, a catchment relaxation time was calculated using temporally constant average meteorological input. The relative importance of the initial conditions varied with the start of the simulation. The maximum detectable influences of initial conditions ranged from 50 days to at least a year. Drier initial conditions of soil moisture and groundwater as well as more initial snow resulted in longer influences of initial conditions. The catchment relaxation varied seasonally for higher elevation catchments, but remained constant for lower catchments, which indicates the importance of snow for streamflow predictability. Longer persistence seemed to also

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stem from larger groundwater storages in mountainous catchments, which may motivate a reconsideration of the sensitivity of these catchments to low flows in a changing climate.

Keywords: streamflow predictability, low flow, ensemble streamflow prediction, reverse ensemble streamflow prediction

1. Introduction

In many parts of the world people are aware of droughts as natural hazards with significant impacts on many sectors especially when they persist for long periods or occur frequently (e.g. Tallaksen and van Lanen, 2004; Dijk et al., 2013; Viste et al., 2013). However, only recently, scientists and stakeholders in Europe have become concerned not only about floods and their forecasting, but also about droughts. Drivers of this increasing interest include recent droughts such as in summer 2003 (Rebetez et al., 2006) and in spring 2011, which have made water rich countries like Switzerland become more aware of impacts and risks related to droughts. So far, the main concerns in Europe regarding droughts are of economic, environmental, and social importance (e.g. Stahl et al., 2012). During and after droughts, conflicts between different water users can become more frequent and water management has to adapt to meet the different interests as well as possible. For these reasons drought early recognition has become an issue. The basic objective of drought early recognition is to provide timely warning, so that damages can be reduced or even avoided. However, little has been done regarding forecasting and early warning of droughts in Europe. The severity of a drought depends clearly on the climatological deficit of water, but also on the hydrological system that has to cope with this deficit. There were many attempts to quantify droughts by indices based on meteorological variables such as the Palmer drought severity index (Palmer, 1965), deciles (Gibbs and Maher, 1967), the surface water supply index (Shafer and Dezman, 1982), the standardized precipitation index (McKee et al., 1993) or the standardized precipitation and evapotranspiration index (Vicente-Serrano et al., 2010). Each of these indices has its own strengths and weaknesses. Drought indices based on meteorological variables are important, but not sufficient to describe and understand the severity of a hydrological drought. Hence, to recognize locally critical conditions early and provide that information to decision makers, requires both information of the climatological anomalies as well as an understanding of the underlying hydrological systems.

The persistence of a system is a measure of how a hydrological condition at a certain point in time can influence the following period and can also be seen as the memory of the system. Catchments with a small storage also usually have a small persistence while catchments with large storages can have longer persistences. The predictability of streamflow and other hydrological variables is highly connected to persistence and there exist various methods to estimate persistences. A classical approach to estimate short term persistence is to calculate the autocorrelation of the time series of streamflow observations (e.g. Vogel et al., 1998; Pagano and Garen, 2005). Applying the autocorrelation to highly seasonal data like streamflow data means that they first need to be de-seasonalized before a signal other than seasonality can be found from the autocorrelation can be found. De-seasonalization procedures for hydrological data, however, often require calibration themselves, as the seasonality rarely corresponds to calendar dates (Hipel and McLeod, 1994).

Several recent studies try to quantify the impact of initial conditions on the predictability of hydrological conditions. Snow cover (Gobena and Gan, 2010; Mahanama et al., 2012), catchment size (Li et al., 2009), North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO) driven by the Sea Surface Temperature (SST) (e.g. Bierkens and Van Beek, 2009) are generally found to be sources of predictability and they are all highly dependent on the region, system and season. While temperature and precipitation are in part predictable because of the low-frequency variability in global energy stores, particularly in the ocean, (Westra and Sharma, 2010; Feng et al., 2011), on a local scale there are feedbacks because of, for instance, albedo or catchment moisture storages that affect the partitioning between sensible and latent heat fluxes. Predictability in streamflow is controlled by storages, including snow, soil moisture and groundwater, which attenuate the high-frequency rainfall variability to a lower-frequency streamflow response. Singla et al. (2012) assessed the predictive skill of seasonal hydrological forecast in France with two experiments looking at the influence of land surface initial states on the one hand and atmospheric forcing on the other hand. They focused on the spring season as it is critical to the onset of low flows and droughts. One of their important findings was that the predictability of hydrological variables in France mainly depends on temperature and precipitation in lower elevation areas and mainly on snow cover in high mountains. We built on these studies by looking at the predictability of streamflow with focus on low flows in Switzerland using a conceptual hydrological model. These models

are important tools in hydrology as they are able to capture dominant catchment dynamics while remaining parsimonious and computationally efficient (Kavetski and Kuczera, 2007). Conceptual hydrological models can reach, for specific purposes, considerable performance and, thanks to their computational efficiency, can also be used in ensemble prediction systems (Cloke and Pappenberger, 2009). In flood forecasting systems conceptual models like the NAM model (Van Kalken et al., 2004), the Sacramento model (Grijsen et al., 1993), the PDM model (Moore and Jones, 1997) and the HBV model (Bürgi, 2002) are often applied and use for low flow ensemble forecasting is also emerging (Fundel et al., 2013).
In this study we used the HBV model (Bergström, 1992; Lindström et al., 1997) to perform streamflow simulation experiments and to answer the following questions: How long is the persistence of the initial hydrological state in model simulations of streamflow and does it vary in space and time? Can the persistence be attributed to catchment storage?

2. Data and Methods

2.1. Data

The catchments investigated in this study are meso-scale (3 to 350 km^2), near natural catchments located in Switzerland (Figure 1). The mean elevation of the catchments ranges between 480 m a.s.l. and 2400 m a.s.l. (Table 1). Henceforth, specific catchments are referred to by catchment numbers (Table 1). The data used are daily streamflow from the selected Swiss catchments over the period 1970 to 2008 (FOEN , 2011). The meteorological forcing variables for the HBV model, precipitation and temperature, stem from interpolated observations from climate stations (MeteoSwiss) in Switzerland. The selection of the meteorological stations as well as interpolation and aggregation of the variables for each catchment were carried out by the pre-processing tool WINMET (Viviroli et al., 2009). In brief, the spatial and temporal interpolation of observed meteorological variables was based on elevation-dependent regression, inverse distance weighting, Kriging and a simple elevation lapse-rate for temperature data (more details can be found in Viviroli et al. (2009)). A clear seasonal variation of precipitation can be observed for the catchments included here, with winter months receiving about half of the precipitation compared to summer months. The inter-annual variation is similar for all months and about twice as large as the seasonal variation.

2.2. Methods

To quantify the persistence of current hydrological states in streamflow and the influence of weather during prediction we set up three model experiments using the hydrological model HBV in the version HBVlight (Seibert and Vis, 2012) (Figure 2).

2.2.1. Model calibration

The HBV model was calibrated for each catchment with the genetic calibration algorithm (GAP), which is included in HBVlight (Seibert and Vis, 2012). With GAP, optimized parameter sets are found by an evolution of parameter sets using selection and recombination (Seibert, 2000). An ensemble of 100 parameter sets was generated for each catchment, based on 100 calibration trials. The mean absolute relative error, F_{MARE} (eq. 1), served as the objective function for the calibration, as the emphasis was on low to medium flows. Its values range between minus infinity and the optimum at one.

$$F_{\mathrm{MARE}} = 1 - \frac{1}{n}\sum_{i=1}^{n}\frac{|Q_{\mathrm{obs}}(i) - Q_{\mathrm{sim}}(i)|}{Q_{\mathrm{obs}}(i)} \tag{1}$$

2.2.2. Estimation of persistence and catchment relaxation

The model input consists of time series of daily precipitation and temperature as well as mean monthly potential evapotranspiration (Penman, 1948). The first two experiments a) and b) were set up much like the experiments in the study of Shukla and Lettenmaier (2011) and the ensemble streamflow prediction (ESP) and the reverse ensemble streamflow prediction (ESP_{rev}) approach of Wood and Lettenmaier (2008) (Figure 3). However, in this study 100 parameterizations were used for each ensemble member, which allows more robust interpretation by using the ensemble mean as well as quantification of parameter uncertainty effects. Experiments a) and b) evaluate both the influence of initial conditions and weather during prediction on the prediction skill.

The simulation experiments differed in the time series that were used as warming up periods to derive initial conditions, and the time series that were used during the prediction period. In experiment a), during the warming up phase the HBV model was forced with different meteorological time series and the forcing during the prediction was the climatology for all simulations. The climatology, i.e., the long term mean annual series of precipitation and temperature, was computed as 365 arithmetic means of the different years. Experiment b) was the reversed version of experiment a); the time series had identical initial conditions, stemming from the climatology. In the simulations (365 days each), the HBV model was forced with different meteorological time series to derive 'predictions' (Figure 3). For both experiments reference runs were performed: in experiment a) the long term mean was used for both warming up and simulation, in experiment b) the same year as in the experimental run was used for the simulation and the previous chronological year was used for the warming up period. By comparison to reference simulations, the two experiments can serve to estimate streamflow persistences that can again be an estimate of the potential streamflow predictability.

A third experiment was designed to distinguish further between the influence of the catchments themselves and the meteorological conditions. A relaxation time for the catchments was calculated, defined as the time needed for the system to reach a new equilibrium after being brought off balance (e.g. Graf, 1977; Ahnert, 1987; Roering et al., 2001). The warming up in experiment c) was the same as in experiment a). The forcing during the simulation was kept constant and the average annual daily precipitation, mean annual temperature and zero evapotranspiration were used. The precipitation was then distributed to correspond to realistic conditions with precipitation on about 30% of the days, i.e., three times the average precipitation was used as forcing on every third day and zero precipitation otherwise. Before running the simulations the initial snow conditions were all set to zero. This was done to remove the influence the melting of accumulated snow had on the relaxation time estimation, which would obviously have lead to longer relaxation times for catchments with large snow storage. Hence, the catchment relaxation time in this study is the streamflow persistence under constant meteorological forcing.

We defined the persistence [days] in the simulated streamflow as the period from the start of the experiment simulation to the point of convergence (absolute average difference equal to 0.002 mm/day) to the respective reference simulation. After convergence there is no impact of the initial conditions visible in the simulations and hence no longer any persistence (see Figure 3). For the case with a first convergence that would later spread for some reason (e.g. snow melt), the last convergence of the simulation period after which no spread occurred was used to estimate the persistence (Figure 3, experiment b)). The relaxation time [days] was the start of the simulation from experiment c) to the point of an equal oscillation of all simulations. All experiments a), b) and c) were repeated four times with a shift in the starting date from winter (January 1) to spring (April 1), summer (July 1) and fall (October 1). The starting date is the time where the initial conditions are set, i.e., the switch from warming up to prediction mode. All analyses were performed for each of the 100 parameter sets and for the persistence estimation as well as the catchment relaxation aggregated to a mean value in the end.

2.2.3. Importance of initial conditions vs. weather during prediction

The "prediction skill" of both experiment a) and experiment b) forecasts were calculated (Shukla and Lettenmaier, 2011). As reference, the reference simulation from experiment b) was used because it is the chronologically correct yearly sequence for each forecast/initial condition. Since we were interested in the effects on low flows, we based the measure of prediction skill of experiment a) (F_{ESP}) and experiment b) (F_{ESPrev}) on the absolute error as also used in F_{MARE} (eq. 2 and 3).

$$F_{ESP} = \frac{1}{n_{ic}} \sum |Q_{ref,b}(t,i) - Q_{sim,a}(t,i)| \tag{2}$$

where n_{ic} is the number of initial conditions (26 different years), $Q_{ref,b}(t,i)$ is the reference of the forecast i at day t and $Q_{sim,a}(t,i)$ is the ensemble member using the initial condition i at day t.

$$F_{ESPrev} = \frac{1}{n_{fc}} \sum |Q_{ref,b}(t,i) - Q_{sim,b}(t,i)| \tag{3}$$

where n_{fc} is the number of forcing ensemble members (26 different years) and $Q_{sim,b}(t,i)$ is the ensemble member at this day and forecast. The time dependent ratio F_{ratio} of F_{ESP} and F_{ESPrev} of each experiment was then calculated using Equation 4.

$$F_{ratio}(t) = \frac{F_{ESP}}{F_{ESPrev}} \tag{4}$$

Values of F_{ratio} larger than one indicate a relatively higher forecast error due to uncertainties in the weather during prediction compared to the uncertainties in the initial conditions. This suggests a high contribution of the weather to the prediction skill (Shukla and Lettenmaier, 2011). Values of F_{ratio} smaller than one indicate relatively larger uncertainties due to the initial conditions compared to the uncertainties in the weather during predictions, which suggests a high contribution of the initial conditions to the prediction skill. The F_{ratio} of all simulations was calculated for lead times of 1, 2, 3, ..., 52 weeks. The values for F_{ratio} were computed for each of the 100 calibrated parameter sets and then aggregated as the mean.

2.2.4. Connection of persistence to conceptual storages

The HBV model consists of a number of conceptual storages: snow storage ($Snow$), soil moisture (SM), upper groundwater (SUZ), and lower groundwater storage (SLZ) (Figure 2). The initial storages at the start of each simulation were compared to the estimated persistences from experiment a). The actual initial hydrological state at the start of each simulation was transformed to a relative initial hydrological state by using the long term average conditions of the respective month in which the simulation start was set. For instance in winter the relative initial state is the ratio of the state on January 1 in a particular simulation and the average January state condition from the entire 26-year-period. The relation of initial conditions of each storage ($Snow$, SM, SUZ, and SLZ) from the 21 years of each catchment to the respective persistences were then analyzed by calculating the Spearman rank correlation between initial state and persistence for each catchment. Correlations with a p value smaller than 0.05 were considered statistically significant.

3. Results

3.1. General model performance

The model performance (F_{MARE}, eq. 1) of the best parameter sets varied between 0.64 and 0.84 for the 21 catchments with a median of 0.77. Good model performance could be achieved with varying individual parameter values and on average the best parameter values for a single catchment varied over 10 to 66 % of the tested parameter ranges.

3.2. Persistence in streamflow simulations

Experiment a) and b) resulted in similar estimates for persistence in streamflow for all catchments ranging between 50 days of persistence to more than a year (Figure 4). There was a tendency of higher elevation catchments to have longer persistences. We found strong correlations between the mean of the persistence estimates and the mean catchment elevations for all seasons (Table 2). The difference in estimates for the different starting dates was small. For spring and summer catchments 9 to 18 have higher persistence estimates for experiment a) than for experiment b). This difference is still visible for the values based on fall simulations, but is not apparent for the winter simulation. The variability of the persistence estimates caused by parameter uncertainty (i.e., the spread among the simulations of the 100 parameter sets) was higher than that caused by the inter-annual variability (i.e., the spread among the simulations for the different years) (Figure 5). Especially simulations starting in summer and fall showed an increased variability from parameter uncertainty for many catchments.

3.3. Catchment relaxation

The catchment relaxations varied between about three months to a year. For the low elevation catchments the catchment relaxation remained the same for all seasons, while the higher elevation catchments showed differences when starting the simulations at different dates. In Figure 6 the estimated mean persistences and the catchment relaxation times are compared. All catchments but catchment 18 have longer persistences than catchment relaxations. The difference between catchment relaxation and mean streamflow persistence was smallest in spring and became larger in summer, fall and winter. The largest difference between relaxation and persistence was seen in fall.

3.4. Importance of initial states vs. weather during prediction

F_{ratio} was found to vary with the season of the start of the simulation for the different catchments (Figure 7). For clarity, it should be mentioned again that the F_{ratio} indicates the relative influence of the initial conditions in comparison to the weather, while the persistence indicates the influence of the initial conditions on the predictions regardless of the weather. In spring, the F_{ratio} with values smaller than one had the longest lead times in most low elevation catchments and the highest elevation catchments with lead times ranging from 8 to 11 weeks. Middle and high elevation catchments have only very short lead times of about a week, during which the initial conditions have greater uncertainties than the weather during prediction. In summer, the length of the lead times with an F_{ratio} smaller than one varied for the catchments, but the pattern could not be clearly related to catchment characteristics. However, many low elevation catchments have an F_{ratio} smaller than one for lead times from 9 to 10 weeks. The shortest lead time with an F_{ratio} smaller than one when starting in summer was one week and the longest lead times with an F_{ratio} smaller than one 12 weeks. In fall, there is a clear tendency of greater uncertainties of the initial conditions for a longer period than those for weather for higher elevations. The shortest lead time with an F_{ratio} smaller than one when starting in fall was five weeks, and the longest lead time 18 weeks. In winter for all but the high elevation catchments the uncertainties of the initial conditions relative to the uncertainties of the weather decreased quickly and for most catchments with an F_{ratio} smaller than one, lead times were at the maximum one to three weeks. For the high elevation catchments the lead times with an F_{ratio} smaller than one ranged from 5 to 19 weeks, and for the three highest elevation catchments with an F_{ratio} smaller than one, the range was from 14 to 19 weeks.

3.5. Hydrological states and streamflow persistence

The main snow accumulation happens in early spring and winter. For most catchments, more snow during the initial conditions in winter were related to longer persistences (Figure 8). The Spearman correlation coefficients ranged between 0.46 and 0.66 for the statistically significant positive correlations in winter (Figure 10). In spring this relationship could only be found for a few catchments. Neither in spring nor in winter, could the catchments with significant correlations be attributed to the catchment properties. In summer only the highest elevation catchments would show snow effects, while in fall there might be single days of single years where snow starts to accumulate. For this reason we looked only at the relation between persistence and snow storage in winter and spring.

Drier initial soil moisture conditions in winter and spring for most catchments were related to longer persistences (Figure 9). The initial conditions of the other seasons showed both positive and negative correlations for different catchments (Figure 10). The negative correlations in spring and winter were found for low and middle elevation catchments. In summer the correlations could not be attributed to catchment properties. However, the positive correlations in fall were mainly found for low elevation catchments, while the negative correlations were rather found for middle and high elevation catchments.

The initial conditions of the upper groundwater storage (SUZ) showed a clear tendency related to the persistence only in spring. Here, drier initial SUZ led to longer persistences for most catchments. There were significant

correlations for the low and high elevation catchments, but not for the middle elevation catchments (Figure 10). The initial conditions in the other seasons were both positively and negatively correlated to the persistence. For winter only very few catchments showed significant correlations between initial conditions and persistence.
The lower groundwater storage (SLZ) with a simulation start in spring showed both significant positive and negative correlations to the persistence (Figure 10). In spring negative correlations were found for low elevation catchments, while the positive correlations did not match patterns of catchment elevation or size. In fall the positive correlations were found for the low elevation catchments, however, the negative correlations did not show any common pattern with catchment properties. In summer and winter, the correlations did not clearly match any catchment property pattern.

4. Discussion

4.1. Hydrological model

The results regarding persistence and relaxation times are to some degree model dependent. However, if a model has been successfully calibrated, differences are probably relatively small. It can be assumed that the important storages as well as their variability relative to each other are reasonably well represented. The model we used here was somewhat less complex than the VIC model (Liang et al., 1994), which has been used in several of the previous studies on persistence (Wood and Lettenmaier, 2008; Shukla and Lettenmaier, 2011). However, the groundwater routines of HBV and VIC are relatively similar. Using a less complex model allowed us to derive several behaviorable parameter sets and in this way to address parameter uncertainty, something that has not been done in the previous studies. From our results the use of an ensemble mean can be recommended, as the variability of the results due to parameter uncertainty was considerable for most of the catchments. The large variability among the simulations that were started in summer and fall when including parameter uncertainty indicates a high uncertainty connected to parameters of the soil routine which control evaporation. Seibert and McDonnell (2010) also concluded that it is important to consider parameter uncertainty to obtain reliable results. A high variability due to parameter uncertainty increases the risk for variable and partly random results if only a single parameter set is used. The ensemble approach used here is a suitable way to ensure robust results.

The simulated snow cover was derived from a degree day method, which could be argued to be less accurate than a snow cover simulated with energy balance methods. However, for the spatial and temporal scales looked at here, several studies have shown that the degree day method is an appropriate approximation (e.g., Rango and Martinec, 1995; Seibert, 1999; Hock, 2003; Merz and Blöschl, 2004)
The formulation of the potential evaporation can yield large differences in evaporative demand which can affect the calibrated model parameters and thus how the moisture is stored (McMahon et al., 2012). However, any errors in the estimation of the potential evaporation is implicitly considered in the calibration, i.e., parameter values might be influenced, but the catchment behavior in terms of responses and persistences should be influenced less. All these issues related to the model choice have to be considered, also when evaluating the results. However, the main outcomes concerning the influence of initial conditions related to storages within the catchment are represented and that the use of various parameter sets allowed for the estimation of uncertainty derived from the model.
Arithmetically averaged precipitation values were used in the climatology time series. While this approach ensures a representative mean precipitation amount, the temporal pattern of precipitation might be changed resulting in more days with some precipitation. During winter this has no effect on the simulated streamflow, but the mean simulated summer streamflow might decrease as more precipitation can be temporarily stored and then be evaporated. However, in the humid catchments used in this study, the effect on the total streamflow volume is limited. While it is important to be aware of this unrealistic temporal pattern in the precipitation climatology time series, its influence on the results of persistence and relaxation times in this study will not be substantial.

4.2. Prediction skill

Mahanama et al. (2012) started their simulations, as we did, in different seasons and looked at the ratios of the prediction skills (F_{ratio}) for several lead times up to six months. They found that depending on when the simulations were started and the lead time applied, the dominance of initial conditions or weather during prediction changed from more dominant initial conditions for short lead times (mostly 1 month) to more dominant weather during prediction for longer lead times. Mahanama et al. (2012) found that during spring and summer months initial conditions dominated the prediction skill in the U.S. beyond short lead times. We looked at the dominant effect at lead times up to one year and found at the shorter lead times relatively larger uncertainties stemming from the initial conditions and more uncertainties from the weather overall as compared to the initial conditions for all starting dates, which is similar to the findings of Mahanama et al. (2012) and the observations by Wood and Lettenmaier (2008) for the North Western US. However, the distribution of the F_{ratio} changed for different starting dates and for some catchments even more strongly. Shukla and Lettenmaier (2011) noted differences in the ratio of their objective functions for varying dry or wet initial conditions. We observed this as well, as the rather wet initial conditions in spring showed a dominant contribution of the weather during the prediction on the skill for the lower and highest elevation catchments. This changed for the drier initial conditions found in summer, where the uncertainties of the initial conditions are larger for longer compared to the uncertainties of the weather than in spring.

4.3. Variability of the persistence estimation

From the two experiments, the different model parameter sets for the simulations and the different seasonal forecasts as well as initial conditions, we found a distribution of persistence estimates for each catchment. The persistence estimates from experiment a) and experiment b) overlapped for most catchments. The persistence estimations from experiment b) were systematically longer in spring and summer for all catchments than the persistences from experiment a). In experiment a), the experiment run as such is a representation of what we face in reality, an attempt to forecast using a known initial condition and several scenarios of how the weather might be. By using reference simulations based on the true weather, this gave us the opportunity to see how long a present/initial state mattered in deriving the most realistic simulation rather than simply initializing the model with the climatology. Instead, in the reference of experiment a) both warming up and forcing was with the climatology. So, the persistences in experiment a) were computationally much faster to estimate than in experiment b) but the climatology plays a greater role in the definition of the persistence estimation. The role of climatology could be the reason for the observed offset in the persistence estimates for the middle elevation catchments: If the initial conditions were wetter and/or more snow accumulation took place during the models warming up phase, it would take longer to reach the reference simulation that was based on a drier climatology than it would take to reach a reference simulation that was based on a realistic seasonal warm up (as in the reference runs from experiment b)). For fall and winter simulations the climatology was likely closer to a realistic seasonal warm up, since we could not observe this offset for those seasons.

4.4. Streamflow persistence vs. catchment relaxation

The estimated streamflow persistences are a combination of both weather and catchment properties. Catchment relaxation times should instead mainly represent the catchment storage properties. The relaxation times in different seasons however can vary slightly as the simulations started with different initial conditions each season and then reached a new balance of the system. The catchment relaxation time for catchments with a snow dominated streamflow regime were longer in spring compared to the other seasons, which could be explained by filled soil and groundwater storages from the preceding winter and fall. Since the lower elevation catchments did not show this seasonal difference we suspect the higher catchments to have larger storages.

4.5. Initial conditions and catchment properties

We found that the persistence estimates were strongly correlated to catchment mean elevation. This could partly be explained by an increasing snow influence with elevation, but could also be due to larger aquifers. In the synthetic experiments of Van Loon et al. (2014), who compared warmer and colder climates as well as the effect of varying geology, both increased snow influence and slower aquifer response were found to cause longer drought persistences. In our study, we also found that initial storages of snow and soil moisture were related to the persistence estimates, which corresponds to the conclusion of Van Loon et al. (2014) that seasonality effects cannot be explained by meteorological processes alone. The relation between storage of snow/soil moisture and persistence was also found by Singla et al. (2012) for France and by Mahanama et al. (2012) for the U.S.. While Singla et al. (2012) could distinguish between the importance of snow and soil moisture for elevation classes, we did not find such a clear signal. Instead we saw that the importance of snow, soil moisture and groundwater storage, depended on the starting date of the simulations. When the simulations were started in winter or spring the initial conditions of snow were related to the persistence estimates for many catchments and in summer to the highest with more initial snow leading to longer persistences. Drier initial soil moisture could be connected to longer persistences for lower elevation catchments with simulation starts in all seasons but winter. Longer predictabilities connected to drier initial conditions were also found by Fundel et al. (2013). For higher elevation catchments and winter simulation start wetter initial conditions lead to longer persistences. This can be explained by the absolute size of the soil moisture storage of lower elevation catchments compared to higher elevation catchments. The persistences and initial groundwater storage conditions did not show a general pattern.

4.6. The role of snow

Accumulating and melting snow is an important storage and storage outflow. Moreover, snow melt fills other storages in the catchment. Hence, when trying to distinguish between meteorological influence and initial conditions with the ESP/ESP_{rev} analysis this double role of snow has to be taken into account. Snow melt that contributed to the initial conditions is attributable to the initial conditions, but snow fall, accumulation and melt during the simulation period will directly influence the meteorological forcing. The high elevation catchments where snow fall could also occur in seasons other than winter showed a different effect than the catchments at middle elevations, where the initial conditions were still more dominant than the meteorological forcing. This could result from the time shift of when the snow accumulation and melt happened.

For the persistence estimation, snow storage is directly taken into account, which was visible in both the correlation to the mean catchment elevation and the relation between snow storage and persistence. For the catchment relaxation, the direct snow accumulation and melt was explicitly excluded, even though the snow melt that occurred during the warm-up was included. This remaining snow influence seems critical as we found seasonal differences in the relaxation times of the middle and higher elevation catchments, but not in the lower elevation catchments.

Another indication for the role of snow can be seen from the already discussed offset between the results from experiment a) and b), namely that the climatology in the warming up of the reference runs in experiment a) were not as realistic as the warm up of experiment b), which caused greater offsets in the seasons with snow involved.

4.7. *Catchment elevation and storage*

At high elevations we usually find thinner soils, however, our results challenge the common assumption of less storage in higher elevation catchments and indicate that there might be a larger groundwater storage. This can be explained by large storage features that can be found in mountain catchments like talus slopes with high storage capacities. The total storage capacity might also increase with elevation because of a storage volume above drainage level that is higher in mountainous catchments than in rather flat low elevation catchments. We know for example that the highest catchment (catchment 21) from our selection shows extraordinarily high storage capacities as water can be stored in deep moraines that make up one third of the entire area and in an additional alluvial storage on the valley floor (FOEN , 2011).

4.8. *Predictability of droughts*

In this study, the analyses were performed from a low flow perspective, as the objective function during both the calibration and the analysis emphasized low flow. The persistence estimations showed that for different catchments the maximum predictability for streamflow varied from 50 days to more than a year with the tendency to show higher elevation catchments related to longer predictabilities. The persistence estimates did not vary greatly with a change of the starting date of the simulations to another season. The relative influence from weather with respect to initial conditions, however, varied with a change of the starting date of the simulations. In spring the highest elevation catchments had longer lead times with small uncertainties of the initial conditions presumably due to large snow accumulations at the start of the simulations for all years of the ensemble. The lower elevation catchments, however, have, at the time of the start of the simulation, barely accumulated snow, while the snow storage at middle elevation catchments might vary strongly from year to year. This can explain the longer relative influence of the initial conditions on the predictability found for the low elevation catchments, but not in the middle elevation catchments, as the snow can accumulate before or after the starting date of the simulation (April 1). In fall and winter higher elevation catchments tended to have longer lead times of high relative importance of the initial conditions compared to the weather during prediction. This points to a larger influence of the initial conditions in higher elevations which could be due to snow storage as well as other storages. With the tendentially drier conditions in summer there was more variation and the simulations of catchments, no matter at which elevation, had longer or shorter small uncertainty contributions from the initial conditions. The summer F_{ratio} point on the one hand to storage differences, but also to varying summer meteorology for the different catchments. With this study, the question of how long before a drought occurs can it be predicted, cannot readily be answered. However, for the catchments in this study we found ranges of maximum detectable influence of initial conditions from 50 days to more than a year. Further, we found that the catchment elevation matters more than the starting date of the simulation for a maximum predictability of streamflow and that the relative importance of initial conditions compared to the relative influence of the weather during the predictions changes with the season in which the simulation start is set.

5. Conclusions

We estimated persistences for 21 different Swiss catchments using model simulation experiments performed with the HBV model. The range of the persistence estimates differed between the catchments and showed a strong correlation with mean catchment elevation. Together with the relative influence of weather with respect to initial conditions, the predictabilities ranged from 50 days to more than a year with a decreasing influence of the initial conditions over time. The degree of the decrease was found to be dependent on the start of the simulation. In fall and winter, a longer influence of the initial conditions during prediction was found for higher elevation catchments as compared to the weather. In spring, the initial conditions were relatively more important for the prediction than weather for the highest and lower elevation catchments compared to the middle elevation catchments. This might be due mainly to annual snow melt and accumulation variations around the starting date of the spring simulations in the middle elevation catchments. In summer, the initial conditions had differing influence on the predictions and were not related to a specific elevation range.

The interpretation of the correlation between higher elevation and longer persistences might not be easy without additional information about catchment properties like type and size of aquifers. Compared to the persistence the relaxation time was lower and the catchment relaxation time varied seasonally for higher elevation catchments but was constant for lower elevation catchments, which indicates the important role of snow in persistence estimation. We found that snow and soil moisture as well as groundwater initial conditions derived from the model states were related to the persistence estimates. Drier initial states of soil moisture and groundwater and more snow accumulation at the start of the simulation led to longer persistence estimates. In opposition to an intuitive expectation from shallow soils in higher elevations, we found an indication for larger groundwater storages in higher elevation catchments. This may motivate a reconsideration of the sensitivity of mountainous catchments to low flows in a changing climate.

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Table 1: Catchment properties (FOEN , 2011).

Number	Catchment	Area $[km^2]$	Mean elevation $[ma.s.l.]$	Regime type	Pores [%]	Fissures [%]	Karst [%]
1	Aach	48.5	480	pluvial	14.9	85.1	0.0
2	Ergolz	261	590	pluvial	10.0	0.0	90.0
3	Murg	78.9	650	pluvial	35.0	65.0	0.0
4	Mentue	105	679	pluvial	77.6	22.4	0.0
5	Broye	392	710	pluvial	65.0	35.0	0.0
6	Langeten	59.9	766	nivo-pluvial	18.3	81.7	0.0
7	Rietholz	3.3	795	nivo-pluvial	0.0	100	0.0
8	Goldach	49.8	833	nival	24.3	75.7	0.0
9	Cassarate	73.9	990	pluvial	0.0	100.0	0.0
10	Sitter	261	1040	pluvial	27.7	39.0	33.3
11	Guerbe	117	1044	nivo-pluvial	77.0	17.7	5.3
12	Kleine Emme	477	1050	nivo-pluvial	50.0	35.0	15.0
13	Sense	352	1068	pluvio-nival	36.7	56.8	6.5
14	Emme	124	1189	nival	12.5	86.5	1.0
15	Grande Eau	132	1560	nival	0.0	60.0	40.0
16	Simme	344	1640	glacio-nival	0.0	75.0	25.0
17	Allenbach	28.8	1856	nivo-glaciaire	48.0	44.5	7.5
18	Riale di Calneggia	24	1996	nivo-pluvial	18.6	81.4	0.0
19	Ova dal Fuorn	55.3	2331	glacio-nival	6.3	14.7	74.0
20	Ova da Cluozza	26.9	2368	glacio-nival	21.3	1.0	77.7
21	Dischma	43.3	2372	glacio-nival	31.2	68.8	0.0

Table 2: Spearman rank correlation between mean catchment elevation and mean of the persistence estimates from experiment a) and b).

Start of simulation	Spearman rank correlation Experiment a	Experiment b
Spring	0.59∗∗	0.90∗∗∗
Summer	0.52∗	0.90∗∗∗
Fall	0.85∗∗∗	0.89∗∗∗
Winter	0.81∗∗∗	0.60∗∗

∗ p<0.05, ∗∗ p<0.01, ∗∗∗ p<0.001

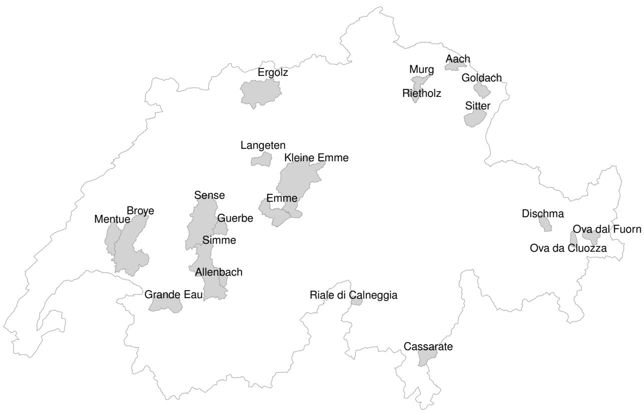

Figure 1: Location of the selected Swiss catchments.

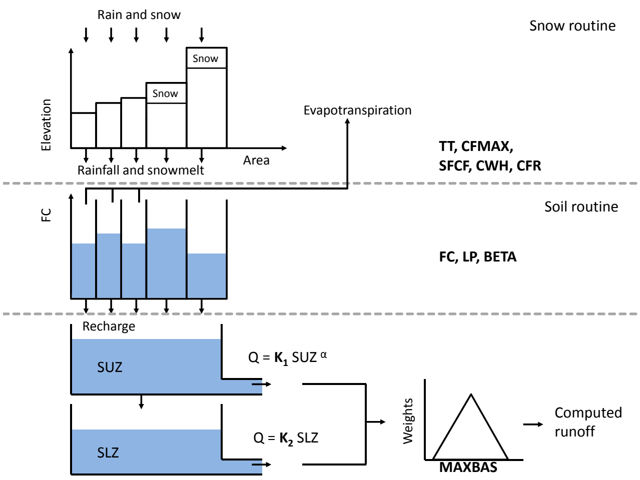

Figure 2: Conceptualization of the HBV model (modified after Uhlenbrook et al. (1999)).

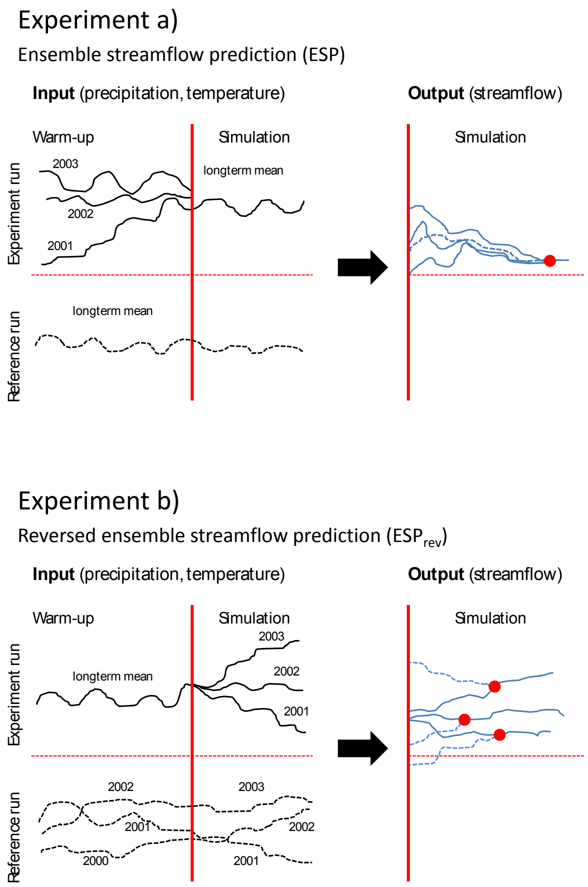

Figure 3: Set up of model experiment a) (ensemble streamflow prediction, ESP) and b) (reverse ensemble streamflow prediction, ESP_{rev}). Dashed lines indicate the reference runs and the red points indicate the persistence.

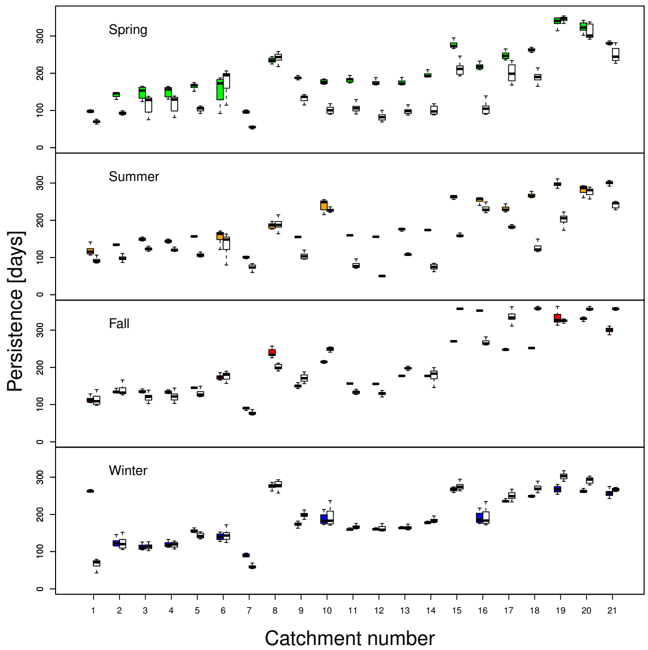

Figure 4: Distributions of the estimations of the persistences from experiment a) and experiment b) for the four starting dates for all catchments. For each catchment two distributions are displayed; the left colored box is the distribution from experiment a) and the right, empty box from experiment b). The catchment mean elevation increases from left to right.

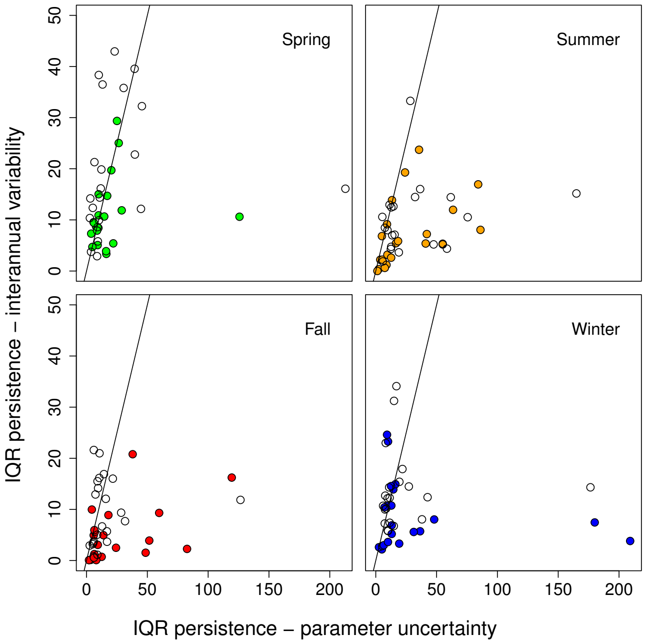

Figure 5: Comparison of the importance of variability of the estimated persistence values due to inter-annual variation and parameter uncertainty. The variability is quantified by the interquartile range, IQR, in the first case computed among the mean values from all 100 parameter sets and in the second case computed from the means of all 26 years. Colored symbols indicate the IQR resulting from experiment a), empty symbols from experiment b).

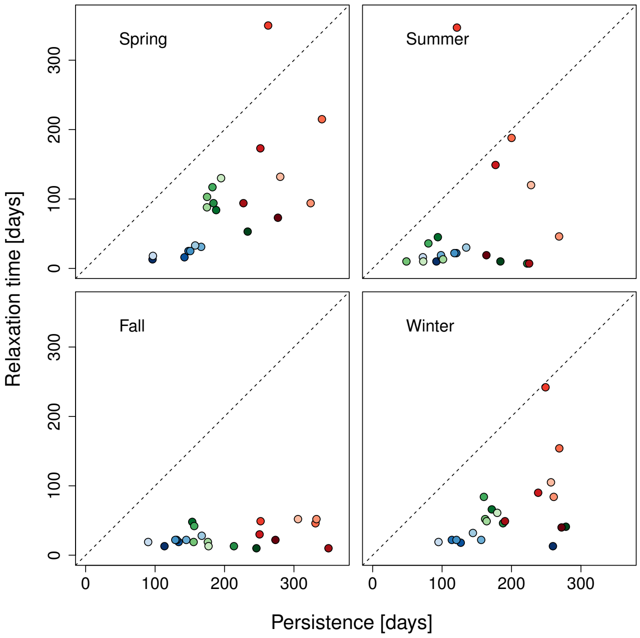

Figure 6: Catchment relaxation times compared to the mean persistence estimates (experiment a)). The colors range from blue for low elevation catchments to red for high elevation catchments.

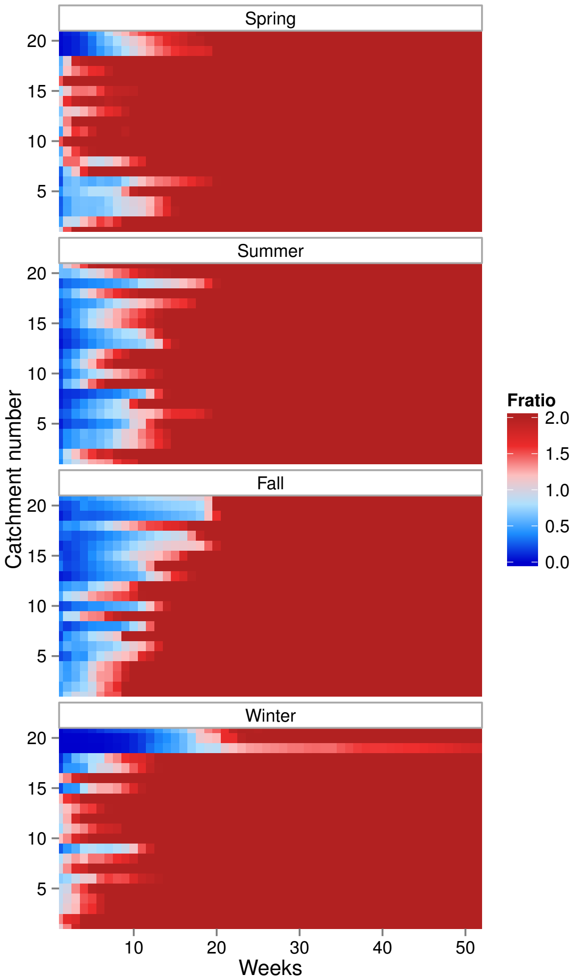

Figure 7: Median of F_{ratio} of the different simulations with lead times starting from one week up to one year in weekly time steps for all catchments and seasons. F_{ratio} values smaller than one, blue colors, indicate a larger uncertainty from the initial condition compared to the weather during the predictions; F_{ratio} values larger than one, red colors indicate a larger uncertainty stemming from the weather during the prediction.

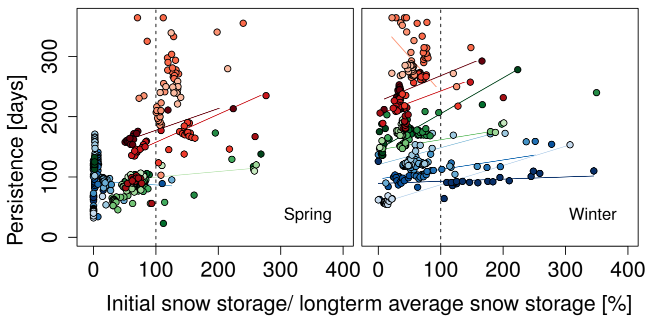

Figure 8: Relation of the initial snow accumulation relative to the snow accumulation during the simulation of the following year and the estimated persistence (experiment a)) for all catchments. Values below 100 indicate that the initial conditions were drier than the average snow accumulation during the simulation. Each color indicates a single catchment and each point a single year. The colors range from blue for low elevation catchments to red for high elevation catchments. For significant rank correlations linear regression lines are drawn.

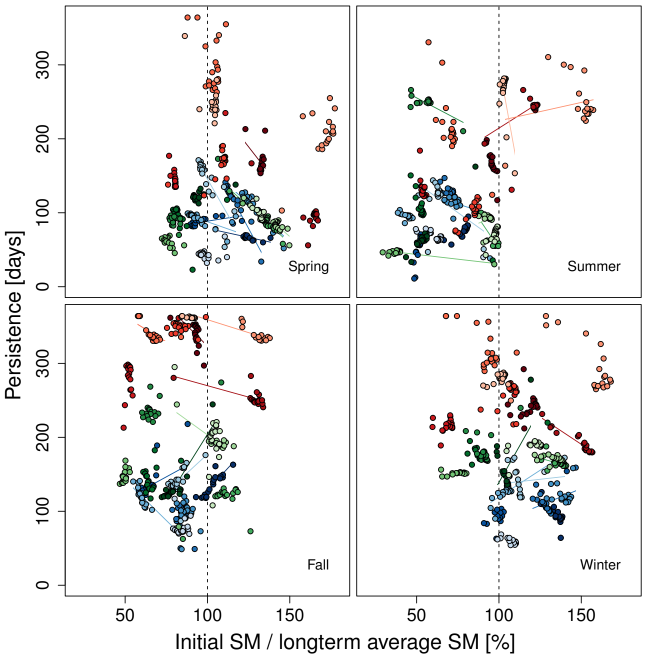

Figure 9: Relation of the initial soil moisture storage relative to the soil moisture storage during the simulation of the following year and the estimated persistence (experiment a)) for all catchments. Values below 100 indicate that the initial conditions were drier than the average soil moisture storage during the simulation. Each color indicates a single catchment and each point a single year. The colors range from blue for low elevation catchments to red for high elevation catchments. For significant rank correlations linear regression lines are drawn.

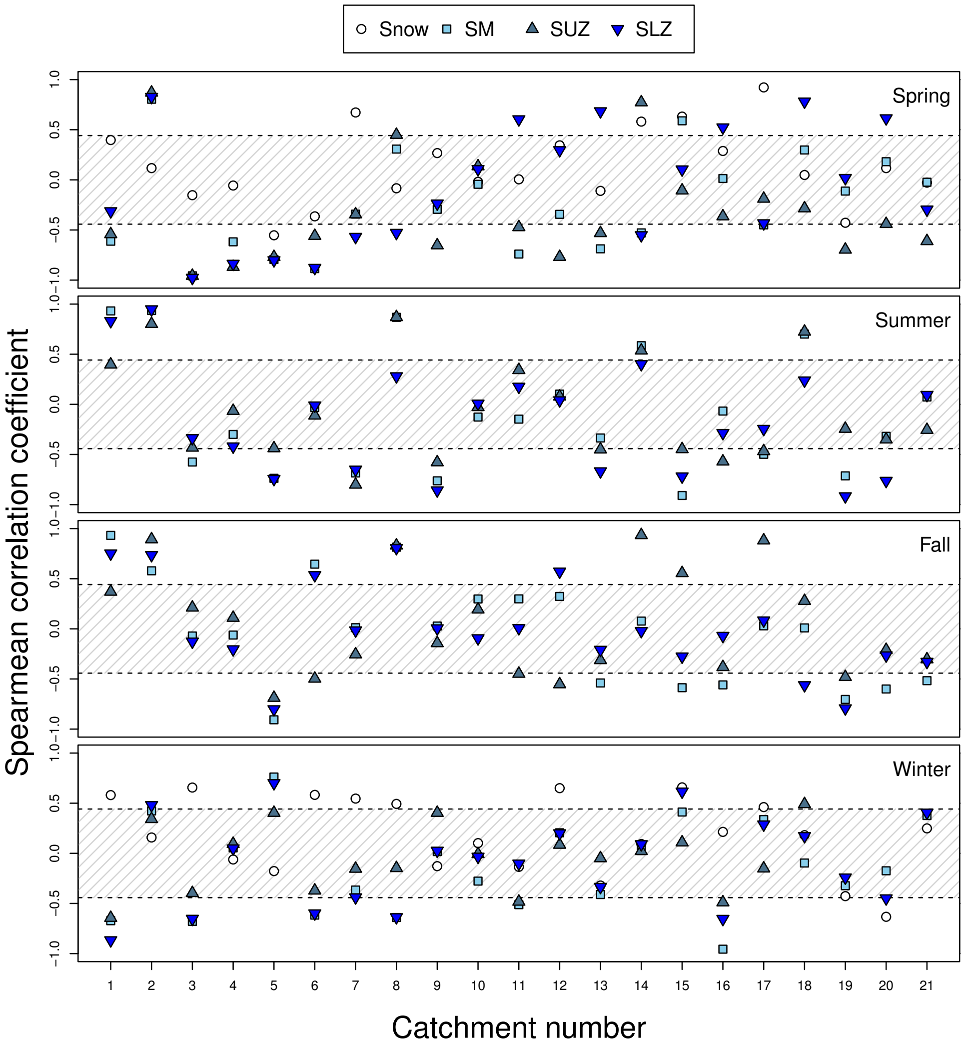

Figure 10: Spearman rank correlation coefficients for the relation between initial conditions of the storages (snow ($Snow$), soil moisture (SM), upper groundwater storage (SUZ) and lower groundwater storage (SLZ)) and persistences (experiment a)). Correlations that are not significant are plotted in the hatched area (p value >0.05).