Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR025903

Key Points:
- Observed discharge time series are usually too short to detect multiyear drought events
- Multiyear drought events can be expected in regions with a rainfall-dominated discharge regime
- Future regime shifts could increase or decrease the proneness of catchments to the occurrence of multiyear droughts

Correspondence to:
M. I. Brunner,
manuela.i.brunner@gmail.com

Citation:
Brunner, M. I., & Tallaksen, L. M. (2019). Proneness of European catchments to multiyear streamflow droughts. *Water Resources Research*, *55*, 8881–8894. https://doi.org/10.1029/2019WR025903

Received 1 JUL 2019
Accepted 3 OCT 2019
Accepted article online 1 NOV 2019
Published online 11 NOV 2019

Proneness of European Catchments to Multiyear Streamflow Droughts

Manuela I. Brunner[1,2] and Lena M. Tallaksen[3]

[1]Mountain Hydrology and Mass Movements, Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland, [2]Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, USA, [3]Physical Geography and Hydrology, University of Oslo, Oslo, Norway

Abstract Droughts can have severe ecological, social, and economic impacts. Some impacts are particularly severe if droughts last longer than 1 year and water stores are not fully replenished. The proneness of European catchments to multiyear droughts has not been studied extensively, even though such events pose a great challenge for water resources management in many regions. In this study, we assess regions and catchments in Europe that might be prone to multiyear droughts by stochastically simulating long discharge records. The simulation approach uses phase randomization and the flexible, four-parameter kappa distribution to generate potential realizations of (long) drought events. Both observed and stochastically simulated series are used to identify multiyear drought events. Catchments prone to multiyear droughts are located in southern France, central Europe, and southwestern England. To assess potential future changes in the proneness to multiyear events, we follow a purely empirical approach. We link the proneness of a catchment to multiyear events to its low-flow regime as described by the seasonality ratio. Our results show that catchments with a melt-dominated flow regime are generally not affected by multiyear droughts, whereas many catchments with a rainfall-dominated flow regime show such proneness. We further find that catchments experiencing regime changes toward a rainfall-dominated flow regime might be more affected by multiyear droughts in the future. Overall, four regions stood out that might potentially become more affected in the future if historical trends in regimes continue: southeastern England, southeastern France, central Norway, and the Pre-Alps.

Plain Language Summary Droughts lasting longer than 1 year can have severe ecological, social, and economic impacts. They are characterized by below-average flows, not only during the low-flow period but also in the high-flow period when water stores such as groundwater or artificial reservoirs are usually replenished. Limited catchment storage might worsen the impacts of droughts and make water management more challenging. Knowledge on the occurrence of multiyear drought events enables better adaptation and increases preparedness. In this study, we assess the proneness of European catchments to multiyear droughts by simulating long discharge records. Our findings show that multiyear drought events mainly occur in regions where the discharge seasonality is mostly influenced by rainfall, whereas catchments whose seasonality is dominated by melt processes are less affected. The strong link between the proneness of a catchment to multiyear events and its discharge seasonality leads to the conclusion that future changes toward less snow storage and thus less snow melt will increase the probability of multiyear drought occurrence.

1. Introduction

Hydrological drought events can have severe ecological and social impacts in addition to negative economic impacts regarding agriculture, energy production, and public water supply (Freire-González et al., 2017; Van Loon, 2015). Unlike many other natural hazards, droughts may persist for long periods and affect large areas. Multiyear droughts have affected Europe several times in the past (Hanel et al., 2018; Parry et al., 2012). However, not all regions are equally prone to the occurrence of such events. The alleviation of drought impacts is possible thanks to natural water stores, including glaciers, snowpack, lakes, groundwater, and soil, as well as artificial stores such as reservoirs (Brunner et al., 2019; Staudinger et al., 2014). Stores are in turn instrumental in supplying water to rivers during low-flow periods controlling—among other processes—the duration of a streamflow drought.

The climate of Europe varies from subtropical to polar. On the ground, the climate signal is modulated by catchment characteristics, in particular, stores such as aquifers, snowpack, and lakes, which determine the hydrological regime. In the Mediterranean region the climate is warm and dry, and streamflow droughts may last several months or even years. Aquifers are replenished in the wet season (winter) in this region, which is crucial for the recovery of the hydrological system. In the more humid midlatitudes of western and northern Europe, summers are mild and droughts typically last for weeks or months, except in regions with large storage systems such as aquifers, where a water deficit may last more than 1 year. Winter precipitation may also be an important water source for vegetation in summer in these regions as recently demonstrated for forest sites in Switzerland (Allen et al., 2019). In northern regions, seasonal snow processes dominate and water stores are normally refilled during the snow melt season, and streamflow droughts are considered seasonal events. If water stores—for example, large aquifers in the south or shallow groundwater in the north—are not fully replenished, the system will be vulnerable to drought in the following dry season or year. Accordingly, the impact of droughts will likely be more severe (Tallaksen et al., 1997) and water resources management will be more challenging (Arena et al., 2006). For these reasons, water managers are particularly interested in long-lasting drought events, that is, those longer than the norm (Abatan et al., 2018).

While most regions in Europe have so far not been affected by multiyear events (e.g., catchments in seasonal snow climates; Tallaksen & Hisdal, 1997), warmer and drier regions such as the Mediterranean have experienced several multiyear droughts (Hisdal & Tallaksen, 2000). Accordingly, future changes in climatic conditions might change the hydrologial regime and thus the proneness of catchments to multiyear droughts.

Climate change is already affecting key components of the water cycle, that is, precipitation, evapotranspiration (ET), and water storage. Temperature increases have led to a decrease in water storage in glaciers (Haeberli et al., 2013) and snow (Kunkel et al., 2016) over the past decades. A future increase in temperature is projected to lead to a further decrease in glacier and snow storage in most regions (Farinotti et al., 2016; Zekollari et al., 2019), with the exception of some high elevation regions where increases in snowpack have already been observed due to increases in winter precipitation falling as snow (Donnelly et al., 2017). The mostly negative changes in snowpack lead to a reduced melt contribution in spring or summer. Precipitation has also changed over the past few decades. Annual precipitation has increased in the northern parts of Europe, while it has decreased in the southern parts and not significantly changed in the midlatitudes (European Environment Agency, 2017). These changes in turn have led to changes and shifts in the seasonality of hydrological regimes, with more discharge in winter, due to more precipitation and a higher fraction of liquid precipitation, but lower discharge in summer, due to less precipitation in this season, earlier snowmelt, and higher ET (Addor et al., 2014; Arnell, 1999). These are trends that are expected to continue in the future as climate warms implying changes in both high and low flows (Barnett et al., 2005; Brunner et al., 2019). Trends in hydrological drought and low flow are already apparent in existing discharge time series, with negative trends in low flows in southern and eastern Europe and generally positive trends elsewhere in Europe (Stahl et al., 2010). These recent changes are expected to become more pronounced in the future. An intensification of streamflow droughts is expected in the south of Europe, whereas a decrease in severity is foreseen for some regions in the north. In the transitions zone, the direction of change is unclear (Forzieri et al., 2014). These expected future changes can be explained by a further increase in annual and winter precipitation in northern Europe and a decrease in annual and summer precipitation in southern Europe (Donnelly et al., 2017; Forzieri et al., 2014; Maraun, 2013).

Future changes in hydrological regime and associated drought characteristics might change the proneness of a region to multiyear droughts. Knowledge on the current and future susceptibility of a region to such drought events enables proactive management of the available resources and increases preparedness. So far, the proneness of catchments to multiyear events has not been assessed on a European scale. This might be related to the fact that observed discharge time series are usually too short to capture the natural long-term variability and accordingly assess the potential occurrence of multiyear droughts (Wijayaratne & Golub, 1991). Natural variability can generate events longer than seasonal droughts that have occurred in the observation period (Parsons et al., 2018). One can obtain sets of plausible but as yet unobserved streamflow sequences using, for example, a stochastic discharge generator that mimics the characteristics of observed data (Borgomeo et al., 2015; Ilich, 2014; Mohan & Sahoo, 2008). Such simulated series may generate potential realizations of droughts, which can be longer than those observed in the historical record.

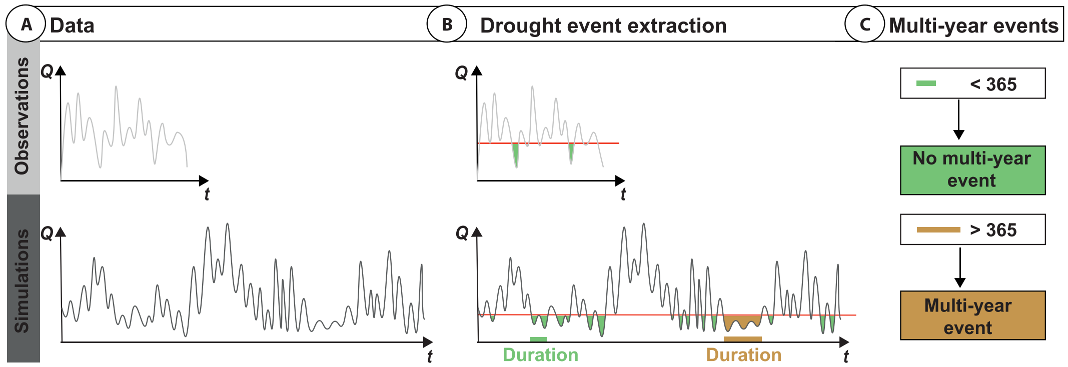

Figure 1. Illustration of assessment framework: (a) stochastic generation of long discharge time (b) drought extraction using the threshold level approach, and (c) determination of the number of multiyear events. The red lines represent the drought thresholds.

In this study, we assessed which regions in Europe might be affected by such rare, multiyear hydrological events, under both current and future climate conditions. To assess the proneness of catchments to multiyear droughts under current conditions, we used long time series generated by a stochastic discharge generator for a large sample of catchments (Figure 1a). The simulation procedure was based on phase randomization, which has been shown to accurately reproduce the temporal and distributional characteristics of observed discharge time series (Brunner et al., 2019). The use of such a long time series helped us identify regional patterns in the current proneness to multiyear drought events. Subsequently, the proneness of a catchment to multiyear droughts was linked to the type of low-flow regime, expressed as the seasonality ratio. The detection of regime changes by analyzing trends in seasonality made it possible to project the susceptibility of catchments to multiyear events into the future since projected future regime changes were found to be rather robust compared to changes in other hydrological signatures (Addor et al., 2014; Schneider et al., 2013).

2. Data and Methods

The proneness of European catchments to multiyear droughts was assessed by identifying drought events in observed and stochastically simulated time series using a threshold level approach (Figure 1). The analysis was based on observed discharge time series of 508 catchments in Europe from the Global Runoff Data Centre (GRDC) (Bundesanstalt für Gewässerkunde bfg, 2019) (Figure 2).

The hydrological regimes of the catchments analyzed were either rainfall or snowmelt dominated with a summer or winter minimum, respectively. The selected catchments had areas between 100 and 1,000 km^2, to avoid including catchments with significant anthropogenic influences, and covered the period 1982–2015 to ensure a large data set. Data for Austria and France were only available until 2012 and were updated via national data platforms (Austria: Bundesministerium Nachhaltigkeit und Tourismus, 2019; France: Ministère de l'Ecologie du Développement durable et de l'Energie, 2019). Data for the Mediterranean region and eastern European countries were not available through GRDC because the stations included did not cover the period under consideration (Laaha et al., 2017). For illustration purposes, we chose a set of six catchments with different streamflow regime and catchment characteristics (Table 1) located at different places within Europe (Figure 2).

We increased the length of the observed discharge time series and therefore the number of drought events by using a stochastic discharge generator (Figure 1a). Stochastic models for generating longer, synthetic streamflow time series should reproduce both the marginal distribution of observed streamflow time series and their temporal dependence structure (Salas & Lee, 2010; Sharma et al., 1997), which encompasses both short- and long-range dependence. Short-range dependence refers to the dependence of daily streamflow values measured within a few days of each other, while long-range dependence refers to dependencies across months or years. Existing streamflow generation approaches have mainly focused on the time domain, even though simulation in the frequency domain offers useful properties including the simulation of both short- and long-range dependence.

10.1029/2019WR025903

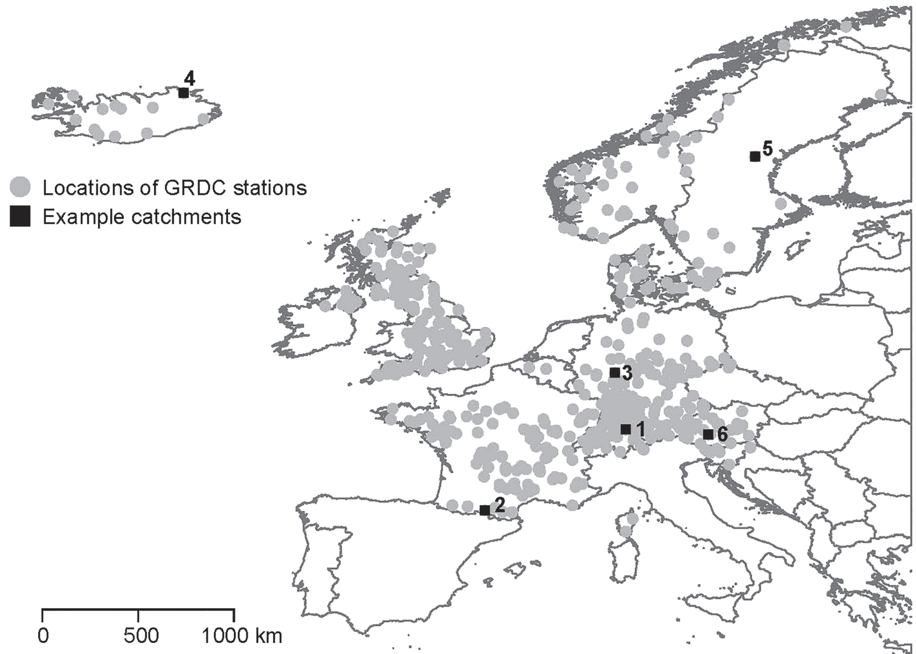

Figure 2. Locations of 508 GRDC stations within Europe. The black squares indicate the locations of the six catchments used for illustration purposes (Table 1).

Simulation in the frequency domain is based on the randomization of the phases of the Fourier transformation. In this study, we generated daily discharge series by applying the simulation procedure proposed by Brunner, Bárdossy, and Furrer (2019), which combines phase randomization simulation (Radziejewski et al., 2000) with the flexible, four-parameter kappa distribution (Hosking, 1994); with this method it is possible to extrapolate to potential realizations of high and low flows. The observed streamflow time series require pretreatment, that is, they need to be normalized, before phase randomization can be applied. The simulation approach consists of seven steps: (1) fitting the theoretical four-parameter kappa distribution to the daily values of the input time series, (2) normalization and deseasonalization of the time series using the normal transformation, (3) Fourier transformation transferring the deseasonalized time series to the Fourier domain and computation of the Fourier phases, (4) random phase generation by sampling from the uniform phase distribution, (5) inverse Fourier transformation after the combination of the random phases with the observed power spectrum, (6) back transformation of the normal data to the kappa distribution using the daily kappa distributions obtained in Step 1, and (7) simulation of time series by repeating Steps 4–7 m times to generate m time series of the same length as the observed time series. The stochastic simulation approach reproduces the temporal correlation structure and distributional statistics of the observed discharge time series and does not impose any nonstationarities. A more detailed description of the approach and its background can be found in Brunner, Bárdossy, and Furrer (2019) and references cited therein. The stochastic simulation procedure is provided in the R-package PRSim, which can be found in the CRAN repository

Table 1
List and Characteristics of Six Catchments Used for Illustration Purposes: Catchment ID (Figure 2), River Name, Station Name, Country, Area (km^2), Elevation (m a.s.l.), and Regime Type

ID	River	Station	Country	Area	Elevation	Regime type
1	Thur	Jonschwil	Switzerland	493	580	Rainfall dominated
2	Arac	Soulan	France	169	541	Rainfall dominated
3	Dill	Asslar	Germany	692	155	Rainfall dominated
4	Sanda	Floegubru	Iceland	266	20	Melt dominated
5	Kassjoean	Storsillret	Sweden	164	224	Melt dominated
6	Taurach	Mauterndorf	Austria	102	1106	Melt dominated

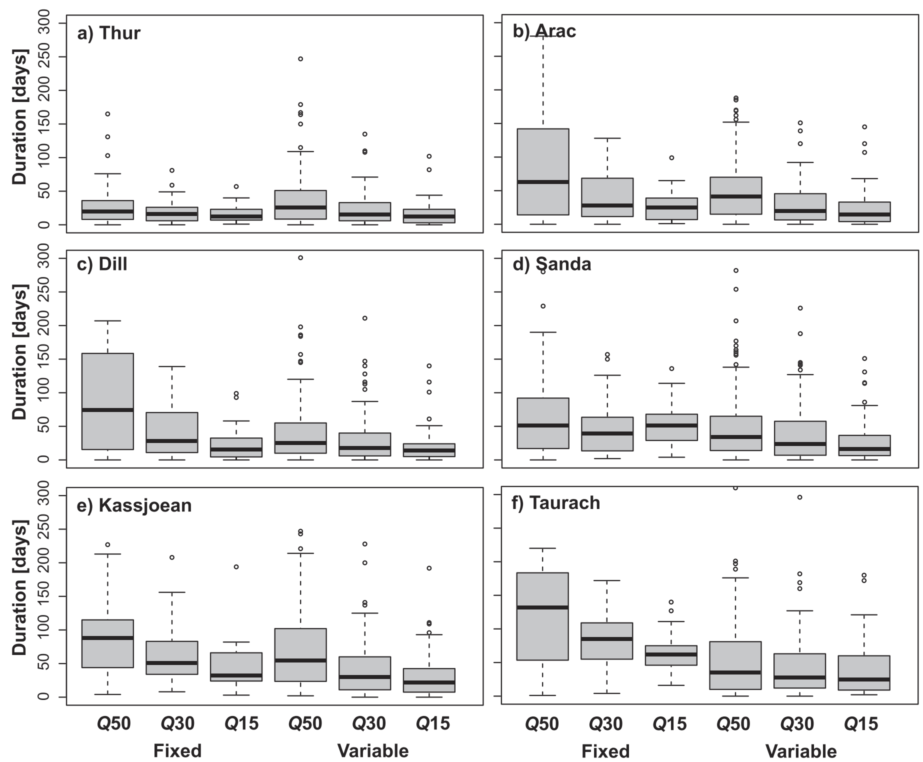

Figure 3. Effect of threshold choice on drought duration for fixed and variable thresholds at the 50th, 30th, and 15th flow percentiles (*Q*50 , *Q*30, and *Q*15) for the six example catchments (Figure 2). (a) Thur, (b) Arac, (c) Dill, (d) Sanda, (e) Kassjoean, and (f) Taurach.

https://cran.r-project.org/web/packages/PRSim/index.html. We applied the phase randomization approach to the observed discharge time series of the 508 catchments to generate a time series of 1,500 years for each catchment representing the current conditions.

The validity of the stochastic simulation approach was assessed by comparing observed and simulated discharge time series with respect to their temporal correlation structure (autocorrelation and partial autocorrelation function) and their seasonal streamflow statistics (distribution, minimum, mean, maximum, and standard deviation). In addition to general distribution characteristics, the approach was validated for drought duration given the focus of the study.

We used both observed and stochastically simulated series to identify drought events using the threshold level approach (Yevjevich, 1967) (Figure 1b), which defines droughts as periods when streamflow does not exceed a certain threshold (Tallaksen et al., 1997). Prior to event extraction, the data were pooled over a moving window of 30 days to avoid the extraction of minor events and limit the number of dependent events (Tallaksen & Hisdal, 1997; Van Loon & Laaha, 2015). This smoothing of the time series ensured that long drought periods, only interrupted by a short rise in streamflow above the threshold, were not separated into individual, dependent events but rather assigned to the same event. Two main ways of defining a threshold exist: fixed for the whole record or varying with season, month, or day of the year. The variable threshold level method detects streamflow deviations not only in the low- but also the high-flow season (Hisdal & Tallaksen, 2000), which are accordingly referred to as streamflow anomalies rather than drought (Tallaksen & van Lanen, 2004). The threshold level should preferably be chosen according to the purpose of the study. We therefore tested different types of thresholds and methods (fixed and variable) and assessed the effect of the threshold choice on the duration of drought events determined using the observed time series. We compared fixed and variable thresholds at the 50th, 30th, and 15th flow percentiles (not exceeded 50%, 30%, or 15% of the time, respectively).

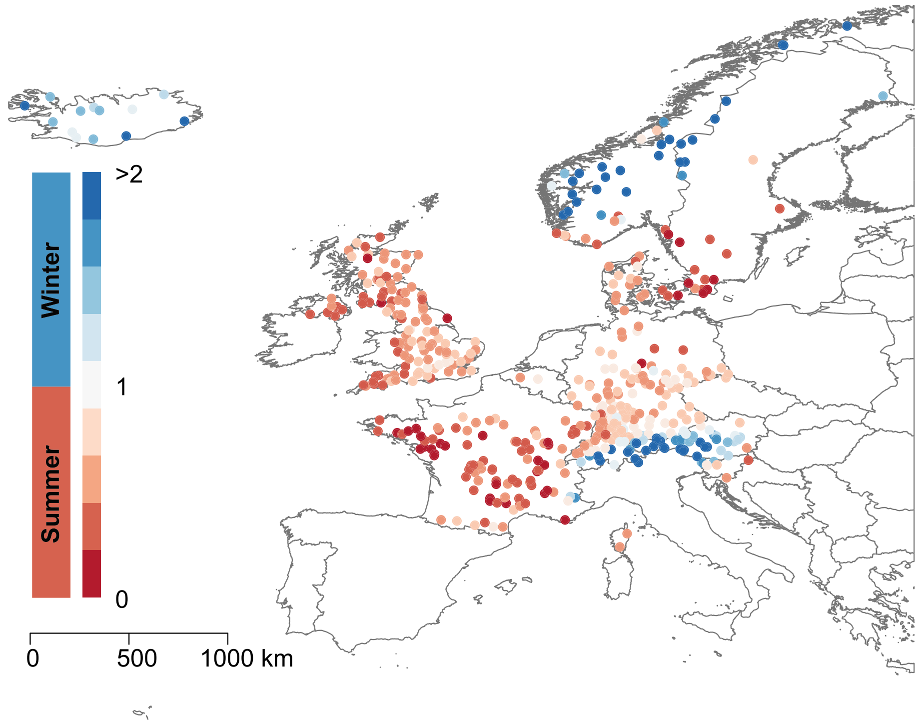

Figure 4. Locations of the 508 catchments included in the study and their seasonality ratio representing their low-flow regime. Red circles indicate summer, that is, rainfall-dominated regimes, while blue circles indicate winter, that is, melt-dominated regimes.

Drought duration was clearly sensitive to the choice of the threshold level (Figure 3). A fixed compared to a variable threshold resulted in longer drought events than a variable threshold except for a few catchments such as the Thur (Figure 3a). The higher the threshold was, the longer was the duration of the events selected. A fixed threshold at the 50th flow percentile led to the longest drought durations among the threshold choices tested. This needs to be kept in mind when interpreting the results regarding the proneness of catchments to multiyear droughts.

Multiyear drought events were hardly identified in the observed discharge time series for thresholds lower than the 50th flow percentile. In accordance with previous studies (Dracup et al., 1980; Parry et al., 2016; Sarailidis et al., 2019; Tallaksen & Hisdal, 1997), a fixed threshold equal to the median flow, that is, the 50th flow percentile, was finally used to determine the number of drought events because we were interested in situations where the average flow conditions in a hydrological system are sustained over a longer period of time. We chose a fixed threshold rather than a variable threshold as our focus was on major drought events occurring in the main low flow season. Among the identified events, those with a duration longer than 365 days were defined as multiyear events (Wijayaratne & Golub, 1991) (Figure 1c). Catchments experiencing at least one multiyear event in either the observed or the stochastically simulated time series were said to be prone to multiyear drought events.

To assess potential future changes in the proneness to multiyear events, we followed a purely empirical approach. We linked the occurrence of multiyear droughts to the low-flow regime type, as described by the seasonality ratio (Laaha & Blöschl, 2006) and hypothesized that past regime changes provide information about the potential future change in the proneness of a catchment to multiyear droughts. Past regime changes in the observed series were used to project potential changes in the proneness of catchments to multiyear events into the future.

The seasonality ratio is the ratio of standardized summer and winter low flows:

$$R_s = q_{05s}/q_{05w}, \tag{1}$$

where q_{05s} represents the 5th percentile of summer flows (May–October) and q_{05w} represents the 5th percentile of winter flows (November–April). R_s values smaller than 1 indicate summer low-flow regimes controlled by precipitation processes, that is, rainfall-dominated regimes, whereas values larger than 1 represent winter low-flow regimes associated with a seasonal snow cover and melt processes in spring/summer, that is, melt-dominated regimes (Figure 4). To detect past changes in the regime type, we computed the trend in R_s for the observed discharge time series over a moving window of 10 years. Trend significance was assessed using the nonparametric Mann-Kendall test (Mann, 1945), which tests for monotonic trends, while the direction and magnitude of the trend were quantified using Sen's slope test (Sen, 1968).

This empirical trend analysis approach avoids the use of a model chain for simulating discharge time series, which usually involves several uncertainty sources. These uncertainty sources include choices of emission scenarios, global and regional climate models, and hydrological models as well as the fitting of their parameters (Clark et al., 2016; Stahl et al., 2012). Climate models have been found to have a limited capability to reproduce the long-term persistence in precipitation (Bunde et al., 2001; Kumar et al., 2013), and low flows are often not well captured by models (Smakhtin et al., 1998; Stahl et al., 2012). Rather, our empirical trend analysis approach is based on the assumption that the direction of past observed trends will persist in the future. This means that we assume that catchments which have experienced a decrease in the seasonality ratio might experience a further decrease, while catchments which have experienced an increase in the seasonality ratio might be affected by a further increase in the future. Changes in regimes, compared to other hydrological signatures, were found to be rather robust (Addor et al., 2014; Brunner et al., 2019; Schneider et al., 2013; Stagl & Hattermann, 2015).

3. Results and Discussion

3.1. Stochastic Simulation

The comparison of long, stochastically simulated to observed discharge time series showed that the phase randomization approach was well able to reproduce the temporal correlation structure as described by the autocorrelation and the partial autocorrelation function and the seasonal statistics as described by seasonal distributions, monthly means, maxima, minima, and standard deviations of the observed data (Figure 5). The autocorrelation is generally well reproduced; the short-term correlation at lag 1, however, is slightly underestimated, which was not a concern here since our focus was on long events. The simulated monthly maxima and minima did not necessarily correspond to the observed ones since the kappa distribution instead of an empirical distribution was used in the simulation procedure, which allows for the extrapolation to low and high values.

The simulated long time series allowed for the generation of drought events with possible but yet unobserved durations (Figure 6). The simulated median duration was similar but overall slightly lower than the observed one. However, notable extreme durations are seen for the simulated series, demonstrating the (potential) occurrence of drought events with yet unobserved long durations, extending up to 2 years. The use of these simulated drought events enabled the determination of catchments prone to multiyear events.

3.2. Proneness to Multiyear Droughts

As expected, relatively few catchments in the observed discharge series were found to be currently prone to multiyear drought events (Figure 7a; 54 catchments). Even in those catchments where we found multiyear events, there were on average only 1.6 such events. The mean duration of multiyear events across all catchments showing multiyear droughts in the observations was 520 days, and the maximum duration determined using observed time series was 1,360 days. Southeastern England, along with a few catchments in southern and western France, southern Germany, and Denmark, stood out as regions affected by multiyear droughts in the past. While only a small proportion of catchments was affected by multiyear events according to the observed time series, many more catchments were found to be potentially affected under current climate conditions when the stochastically simulated discharge series were considered (241 catchments, including those in the observed series). These longer time series suggested that large parts of France, Germany, and Denmark, as well as the northern part of Switzerland and the southern part of England, could be affected by multiyear events under the current climate. In contrast, catchments in Alpine and Nordic regions were not found to be prone to multiyear events (267 catchments). The comparison between multiyear events in observed and simulated series highlights the importance of using stochastically generated time series to detect such rare events, which might not have occurred in the rather short records at hand.

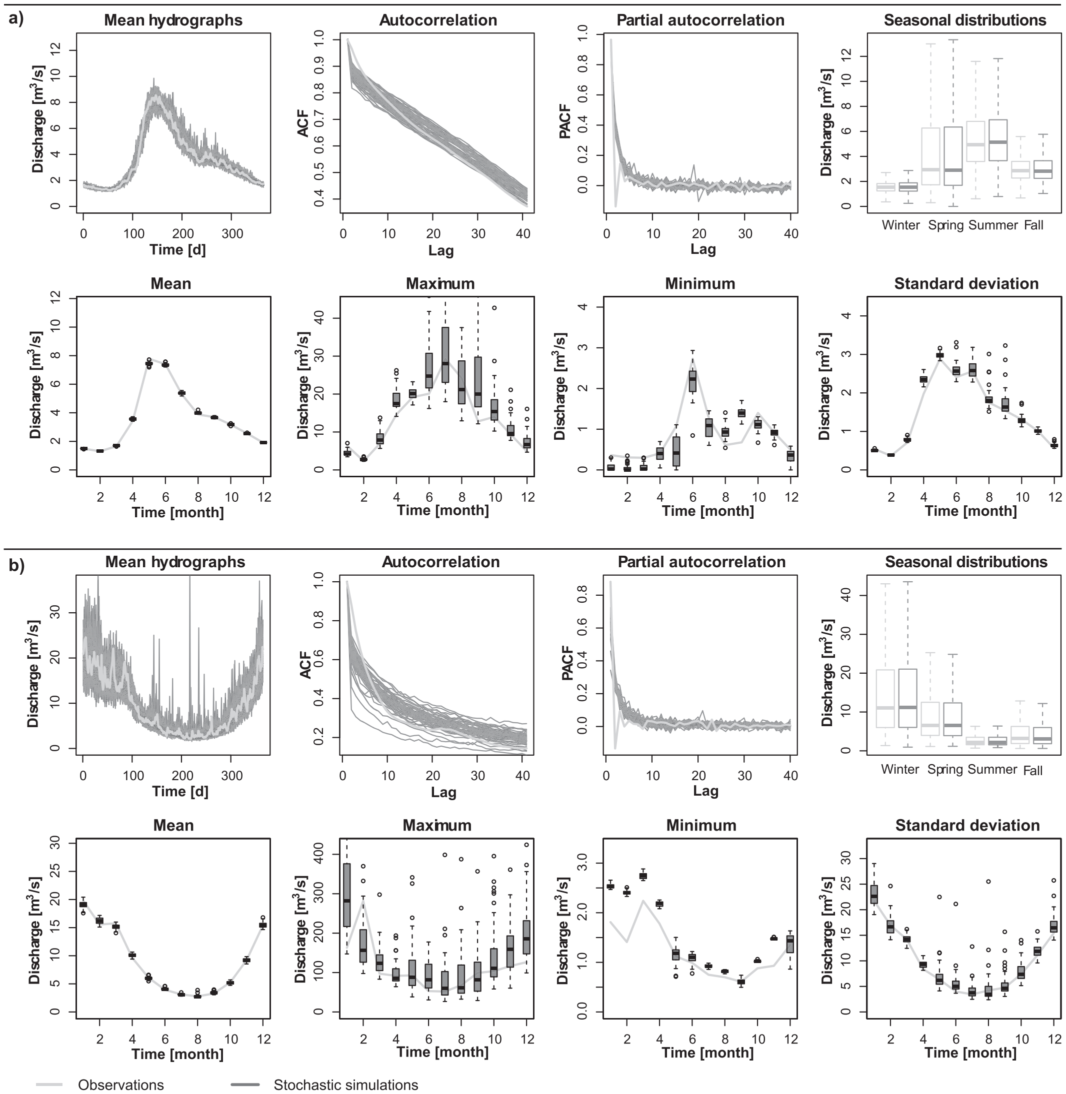

Figure 5. Comparison of observed and stochastically generated time series for (a) the melt-dominated catchment Taurach-Mauterndorf and (b) the rainfall-dominated catchment Dill-Asslar: mean hydrograph over 34 years (length of observed record), autocorrelation function, partial autocorrelation function, seasonal distributions, monthly means, monthly maxima, monthly minima, and monthly standard deviations. Light gray lines represent observations, while dark gray lines represent simulations.

These results agree with findings of previous studies on the spatial variation in drought durations across Europe (Hannaford et al., 2010; Parry et al., 2012). Hannaford et al. (2010) found that droughts in Scandinavia and the Alps are characterized by short durations because streamflow droughts typically end in April–July when snowmelt dominates and stores are refilled. Similarly, Tallaksen and Hisdal (1997) showed that Nordic countries were hardly ever affected by multiyear drought events. This corresponds to our finding that the seasonally snow covered catchments in northern and Alpine regions are currently not prone to multiyear events. The findings of Hannaford et al. (2010) are also in line with our results on regions prone to long drought events. They found drought events lasting between 6 and 12 months in eastern Germany where droughts mainly occur in summer. Furthermore, in our study multiyear events were detected in the central and southern regions of France (Figure 7a), which is characterized by warm, dry summers and where droughts are controlled to a large degree by winter precipitation. Droughts lasting more than 1 year were also identified in southeastern United Kingdom, a region with large aquifers, which was also found to be prone to multiyear droughts in the rather short observed time series.

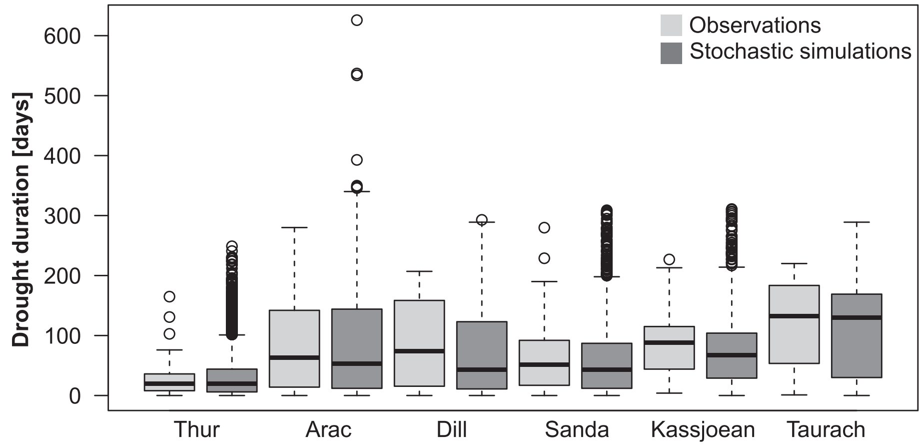

Figure 6. Comparison of drought durations extracted from the observed discharge time series (light gray) and those extracted from the stochastically generated series (dark gray) using a fixed threshold at the 50th flow percentile for the six example catchments (Figure 2). The whiskers of the boxplots extend to the lowest/highest data point which is still within 1.5 times the interquartile range. Outliers are displayed as circles.

Catchments prone to multiyear events were found to be predominantly characterized by a rainfall-dominated regime ($R_s < 1$) (Figure 7b). If a dry summer is preceded or followed by a dry winter, multiyear droughts can develop. We would therefore expect multiyear events in the Mediterranean region which is dominated by rainfall. However, limited data were available for this region including Italy and Spain. In contrast, catchments with a melt-dominated regime and a high-flow period in spring/summer were hardly affected by multiyear events.

3.3. Potential Future Changes in Proneness

The results presented in the previous section suggest that catchments maintaining a melt-dominated regime in the future are unlikely to be susceptible to multiyear droughts. However, some currently melt-dominated catchments might become prone to multiyear drought events if a shift in hydrological regime occurs. Roughly half of the catchments in our data set have already been affected by significant changes in the low-flow regime during the period 1982–2015 (see catchments with changes in Figure 8), and these changes0 (e.g., Sanda) that experience a change toward snow-dominated regimes associated with an increase in streamflow variability (Fountain & Tangborn, 1985). Likewise, some snow-dominated regimes are experiencing a change toward more rainfall-dominated regimes, corresponding to a decrease in R_s, and thus an increase in susceptibility to multiyear events due to a reduced influence of snow accumulation and melt. In contrast, currently rainfall-dominated regimes might experience changes in seasonal precipitation (e.g., more summer rainfall), corresponding to an increase in R_s, and thus become less prone to multiyear events. However, these regimes could also experience less rainfall and thus become more prone to multiyear droughts.

Trend analysis of the seasonality ratios of the observed time series made it possible to group the catchments into five classes with respect to possible changes in their proneness to multiyear drought events if historical trends continue (Figure 8):

(i) Catchments not affected by multiyear drought events under neither current nor future climate conditions (217 catchments). These catchments are currently characterized by a high R_s and show no significant trend in R_s. This class included the Alps, northern England, and large parts of Scandinavia because they are currently—and will continue to be—characterized by a melt-dominated regime.

(ii) Catchments affected by multiyear events under both current and future conditions (87 catchments). These catchments are currently characterized by a low R_s and show no significant trend in R_s. The catchments in this class were spatially very heterogeneous but mostly characterized by rainfall-dominated regimes.

(iii) Catchments potentially less affected by multiyear events under future conditions (78 catchments). These catchments are currently affected by multiyear droughts and are experiencing an increase in R_s. Regions

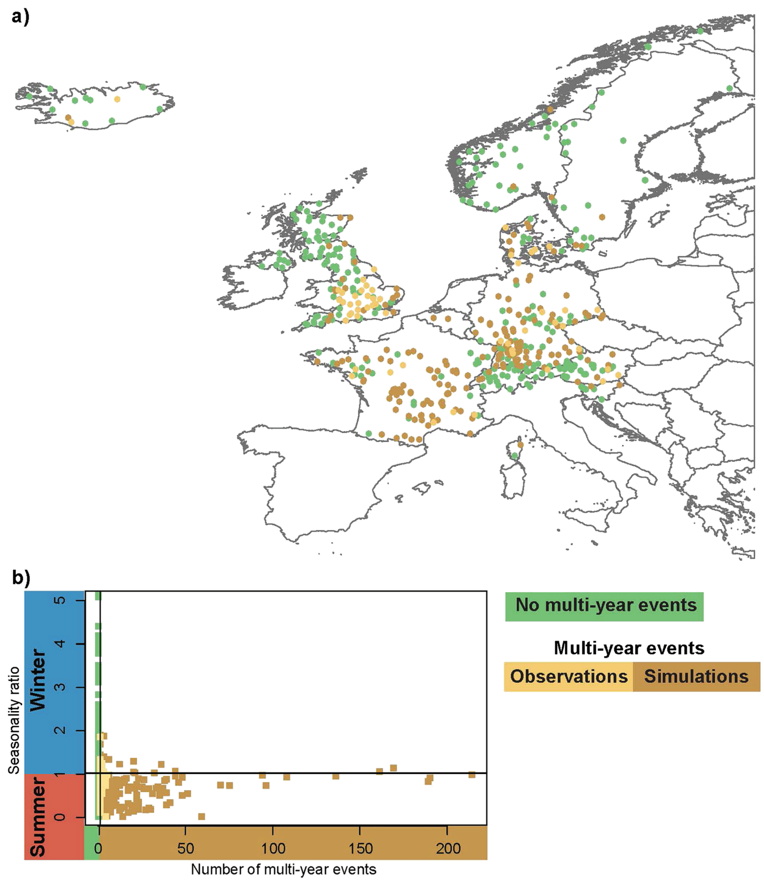

Figure 7. (a) Proneness of catchments to multiyear droughts based on observed and stochastically simulated discharge time series. (b) Relationship between the seasonality ratio and the number of multiyear events identified. In both panels, catchments not prone to multiyear events are shown in green, those prone to multiyear events according to the observed time series in yellow, and those prone to multiyear events according to the simulated time series in brown. The catchments prone according to the observations are also prone according to the simulations.

in this class included northwestern France and northern Germany, regions with rainfall-dominated regimes.

(iv) Catchments potentially affected by multiyear events in the future but not under current conditions (50 catchments). These catchments are currently not affected by multiyear droughts but are experiencing a decrease in R_s. Regions belonging to this class included northern Scandinavia, characterized by melt-dominated regimes, and some regions in the Pre-Alps, which are currently influenced by melt processes.

(v) Catchments potentially more affected by multiyear events in the future than under current conditions (76 catchments). This class comprised catchments currently affected by multiyear events and experiencing a decrease in R_s. Regions belonging to this class mainly included southeastern France and England, which have rainfall-dominated regimes. Not all the catchments prone according to the observed time series were found to become more prone in the future.

Overall, four regions stood out that might potentially become more affected by multiyear droughts in the future if historical trends continue: southeastern England, southeastern France, central Norway, and the Pre-Alps. Southeastern England was found to be prone to multiyear droughts already in the observed time series. This region is characterized by large chalk aquifers, and water management largely relies on groundwater resources (Allen et al., 1997). Southeastern France and some catchments in the Pre-Alps were found to be prone to multiyear droughts according to the simulations, and they showed a change toward more rainfall-dominated regimes. Central Norway was found to be unaffected both in the observed time series and in the stochastic simulations. However, many catchments showed a shift toward more rainfall-dominated

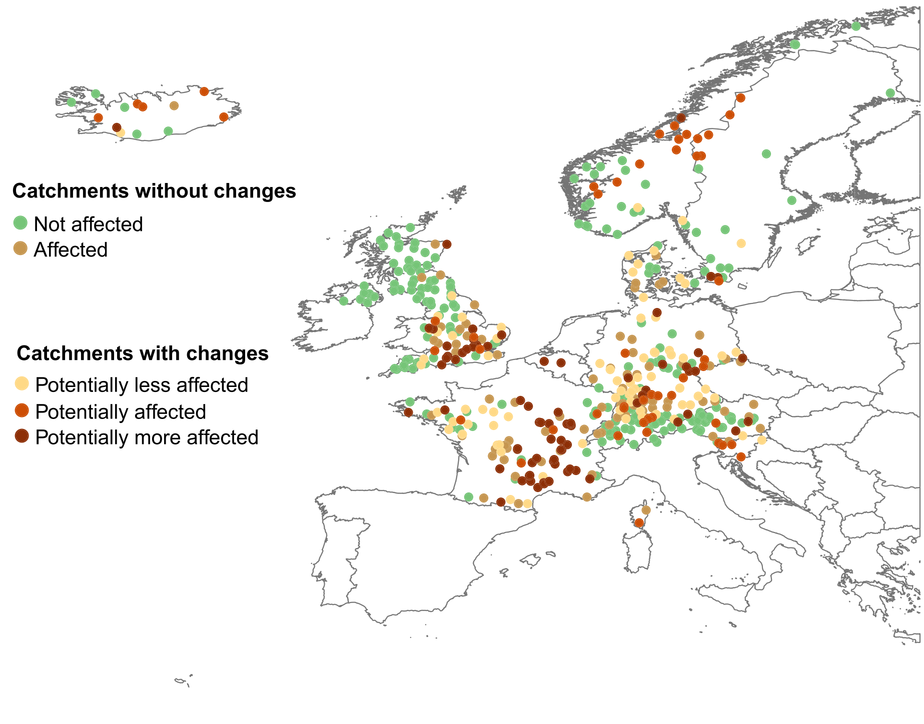

Figure 8. Potential changes in the proneness to future multiyear streamflow drought events grouped by class of change. Catchments that are neither currently nor in the future prone to multiyear events are shown in green (Class i). Catchments prone to multiyear events both currently and in the future, with no change in proneness, are shown in brown (Class ii). Catchments with a decrease (yellow, Class iii) or increase (dark red, Class v) in proneness to multiyear drought events are shown, as well as catchments not currently affected by multiyear events but projected to be affected in the future (bright red, Class iv).

regimes in the future, which related to a decrease in snow cover extent caused by increased warming, as already observed (Rizzi et al., 2017).

Overall, our results regarding potential future changes in the proneness to multiyear droughts agree well with findings from previous studies on expected changes in European droughts. Wong et al. (2011) found an increase in streamflow drought duration for southeastern and northern Norway based on simulations for the period 1971–2100 (HBV model), mainly related to an increase in summer ET. This is consistent with our results that some Nordic catchments might become prone to multiyear droughts in the future if historical trends continue. Giuntoli et al. (2013) detected an increase in drought severity in southern France, in agreement with our finding that this region might become more prone to multiyear events in the future. In contrast, northeastern France might experience a decrease in drought severity (Giuntoli et al., 2013), which is confirmed by our results showing a decrease in the proneness to multiyear droughts in this region. This decrease can be explained by an increasing wetting trend and a related increase in winter low-flows in these regions (Forzieri et al., 2014; Stahl et al., 2012). Overall, it was found that the number of catchments potentially affected by multiyear events in the future, if historical trends in seasonality continue, will be larger than the number of catchments currently affected. This agrees with previous findings of Spinoni et al. (2015) who found a small, but continuous, increase in European catchments prone to drought in terms of precipitation and streamflow.

These regional variations in the current as well as future proneness to multiyear droughts can be explained by regional differences in climate variability and change on the one hand and by differences in catchment characteristics on the other hand (Chikamoto et al., 2017; Parry et al., 2012). Both factors combined impact hydrological regimes and potential changes in the magnitude and timing of future high and low flows and therefore the proneness to multiyear droughts. Hiscock et al. (2011) found that by the end of the century, the increase in (predominantly winter) precipitation in northern Europe will lead to increases in groundwater recharge. However, catchments with limited storage capacity will not necessarily benefit from increased winter precipitation in terms of supporting summer discharge. In contrast, southern Europe is expected to experience lower groundwater recharge due to slightly increased ET and markedly decreased precipitation. The finding that Alpine and Nordic regions, where snow storage plays an important role, are not prone to the occurrence of multiyear events in the future (due to the regular replenishment of catchment stores during winter) highlights a critical role of mountainous and high-latitude regions in the hydrological system in providing water to downstream catchments (Viviroli et al., 2007).

Knowledge on the current and future proneness of a catchment or region to multiyear drought facilitates a reduction in vulnerability by developing suitable water resources management strategies and by increasing preparedness. Our results imply that water managers in rainfall-dominated catchments should be prepared for the occurrence of multiyear events already today, but even more so in the future in some regions and catchments. In these catchments, the importance of reservoirs, that is, artificial stores, might increase because they make it possible to balance seasonal and interannual variability.

4. Conclusions

Stochastic simulation of discharge time series proved useful to assess the proneness of catchments to multiyear drought events, given the rareness of these events. Our results show that catchments prone to multiyear drought events exist in southern France, central Europe, and southwestern England. These catchments have a rainfall-dominated regime, with precipitation mainly falling in winter. In these regions, water management options that alleviate the negative effects of such events should be developed. In contrast, catchments in the Alps and in Nordic countries are not prone to multiyear drought. They profit from a streamflow regime dominated by melt processes in spring and summer that replenish water stores. If historical trends in regime changes continue, a slight increase in the number of regions affected by multiyear drought is expected in the future because regime changes toward more rainfall-dominated regimes and a more pronounced seasonality for rainfall-dominated regimes can lead to changes in the proneness of catchments to multiyear droughts. Catchments dominated by melt processes from snow and glaciers will still not be prone to multiyear events, thanks to their high elevation and high latitude locations. Knowledge on the proneness of a catchment to multiyear events enables managers to adjust water management strategies accordingly.

Acknowledgments
We thank the Global Runoff Data Centre for providing discharge data, Jean-Philippe Vidal for collecting and providing data for the French catchments, and the Austrian Ministry of Sustainability and Tourism for providing data for the Austrian catchments. The GRDC data can be accessed online (via https://www.bafg.de/GRDC/EN/Home/homepage&urluscore;node.html). We acknowledge financial support from the Swiss Federal Office for the Environment (Contract 15.0003.PJ/Q292-5096). We also thank Luzi Bernhard for his help in setting up the stochastic simulations on a server. The study contributes to the UNESCO-IHP FRIEND-Water Programme. We furthermore thank the three anonymous reviewers for their constructive feedback.

References

Abatan, A. A., Gutowski, W. J., Ammann, C. M., Kaatz, L., Brown, B. G., Buja, L., et al. (2018). Statistics of multi-year droughts from the method for object-based diagnostic evaluation. *International Journal of Climatology*, *38*(8), 3405–3420. https://doi.org/10.1002/joc.5512

Addor, N., Rössler, O., Köplin, N., Huss, M., Weingartner, R., & Seibert, J. (2014). Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. *Water Resources Research*, *50*, 1–22. https://doi.org/10.1002/2014WR015549

Allen, D., Brewerton, L., Oleby, L., Gibbs, B., Lewis, M., MacDonald, A., et al. (1997). The physical properties of major aquifers in England and Wales. Keyworth, Nottingham: British Geological Survey. http://nora.nerc.ac.uk/13137/

Allen, S. T., Kirchner, J. W., Braun, S., Siegwolf, RolfT. W., & Goldsmith, G. R. (2019). Seasonal origins of soil water used by trees. *Hydrology and Earth System Sciences*, *23*(2), 1199–1210. https://doi.org/10.5194/hess-23-1199-2019

Arena, C., Cannarozzo, M., & Mazzola, M. R. (2006). Multi-year drought frequency analysis at multiple sites by operational hydrology—A comparison of methods. *Physics and Chemistry of the Earth*, *31*(18), 1146–1163. https://doi.org/10.1016/j.pce.2006.03.021

Arnell, N. W. (1999). The effect of climate change on hydrological regimes in Europe. *Global Environmental Change*, *9*(1), 5–23. https://doi.org/10.1016/S0959-3780(98)00015-6

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. https://doi.org/10.1038/nature04141

Borgomeo, E., Farmer, C. L., & Hall, J. W. (2015). Numerical rivers: A synthetic streamflow generator for water resources vulnerability assessments. *Water Resources Research*, *51*, 5382–5405. https://doi.org/10.1002/2014WR016259

Brunner, M. I., Bárdossy, A., & Furrer, R. (2019). Technical note: Stochastic simulation of streamflow time series using phase randomization. *Hydrology and Earth System Sciences*, *23*, 3175–3187. https://doi.org/10.5194/hess-23-3175-2019

Brunner, M. I., Björnsen Gurung, A., Zappa, M., Zekollari, H., Farinotti, D., & Stähli, M. (2019). Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. *Science of the Total Environment*, *666*, 1033–1047. https://doi.org/10.1016/j.scitotenv.2019.02.169

Brunner, M. I., Farinotti, D., Zekollari, H., Huss, M., & Zappa, M. (2019). Future shifts in extreme flow regimes in Alpine regions. *Hydrological Earth System Sciences*, *23*, 4471–4489. https://www.hydrol-earth-syst-sci.net/23/4471/2019/

Bunde, A., Havlin, S., Koscielny-Bunde, E., & Schellnhuber, H.-J. (2001). Scaling in the atmosphere: Global laws of persistence and tests of climate models. *Physica A*, *302*, 255–267. https://doi.org/10.1142/s0218348x03001860

Bundesanstalt für Gewässerkunde bfg (2019). Global runoff data centre. Retrieved from https://www.bafg.de/GRDC/EN/02&urluscore;srvcs/21&urluscore;tmsrs/riverdischarge&urluscore;node.html

Bundesministerium Nachhaltigkeit und Tourismus (2019). eHYD. Retrieved from https://ehyd.gv.at/

Chikamoto, Y., Timmermann, A., Widlansky, M. J., Balmaseda, M. A., & Stott, L. (2017). Multi-year predictability of climate, drought, and wildfire in southwestern North America. *Scientific Reports*, *7*, 1–12. https://doi.org/10.1038/s41598-017-06869-7

Clark, M. P., Wilby, R. L., Gutmann, E. D., Vano, J. A., Gangopadhyay, S., Wood, A. W., et al. (2016). Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports*, *2*(2), 55–64. https://doi.org/10.1007/s40641-016-0034-x

Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., & Ludwig, F. (2017). Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. *Climatic Change*, *143*(1-2), 13–26. https://doi.org/10.1007/s10584-017-1971-7

Dracup, J. A., Lee, K. S., & Paulson, E. G. (1980). On the definition of drought. *Water Resources Research*, *16*(2), 297–302. https://doi.org/10.1007/s13752-017-0263-9

European Environment Agency (2017). Mean precipitation. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/european-precipitation-2/assessment

Farinotti, D., Pistocchi, A., & Huss, M. (2016). From dwindling ice to headwater lakes: Could dams replace glaciers in the European Alps? *Environmental Research Letters*, *11*(5), 054022. https://doi.org/10.1088/1748-9326/11/5/054022

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., & Bianchi, A. (2014). Ensemble projections of future streamflow droughts in Europe. *Hydrology and Earth System Sciences*, *18*(1), 85–108. https://doi.org/10.5194/hess-18-85-2014

Fountain, A. G., & Tangborn, W. V. (1985). The effect of glaciers on streamflow variations. *Water Resources Research*, *21*(4), 579–586. https://doi.org/10.1029/WR021i004p00579

Freire-González, J., Decker, C., & Hall, J. W. (2017). The economic impacts of droughts: A framework for analysis. *Ecological Economics*, *132*, 196–204. https://doi.org/10.1016/j.ecolecon.2016.11.005

Giuntoli, I., Renard, B., Vidal, J.-P., & Bard, A. (2013). Low flows in France and their relationship to large-scale climate indices. *Journal of Hydrology*, *482*, 105–118. https://doi.org/10.1016/j.jhydrol.2012.12.038

Haeberli, W., Paul, F., & Zemp, M. (2013). Vanishing glaciers in the European Alps. *Pontifical Academy of Sciences, Scripta Varia*, *118*, 1–9. https://doi.org/10.5167/uzh-83973

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., & Kumar, R. (2018). Revisiting the recent European droughts from a long-term perspective. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-27464-4

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., & Prudhomme, C. (2010). Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. *Hydrological Processes*, *25*(7), 1146–1162. https://doi.org/10.1002/hyp.7725

Hiscock, K., Sparkes, R., & Hodgson, A. (2011). Evaluation of future climate change impacts on European groundwater resources, (1st ed.). In H. Treidel, J. L. Martin-Bordes, & J. J. Gurdak (Eds.), *Climate change effects on groundwater resources. A global synthesis of findings and recommendations* (Vol. 27, pp. 351–365). Leiden: CRC Press.

Hisdal, H., & Tallaksen, L. M. (2000). Drought event definition (Tech. Rep. No. 6). Oslo: University of Oslo.

Hosking, J. R. M. (1994). The four-parameter kappa distribution. *IBM Journal of Research and Development*, *38*(3), 251–258.

Ilich, N. (2014). An effective three-step algorithm for multi-site generation of stochastic weekly hydrological time series. *Hydrological Sciences Journal*, *59*(1), 85–98. https://doi.org/10.1080/02626667.2013.822643

Kumar, S., Merwade, V., Kinter, J. L., & Niyogi, D. (2013). Evaluation of temperature and precipitation trends and long-term persistence in CMIP5 twentieth-century climate simulations. *Journal of Climate*, *26*(12), 4168–4185. https://doi.org/10.1175/JCLI-D-12-00259.1

Kunkel, K. E., Robinson, D. A., Champion, S., Yin, X., Estilow, T., & Frankson, R. M. (2016). Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change Reports*, *2*(2), 65–73. https://doi.org/10.1007/s40641-016-0036-8

Laaha, G., & Blöschl, G. (2006). Seasonality indices for regionalizing low flows. *Hydrological Processes*, *20*(18), 3851–3878. https://doi.org/10.1002/hyp.6161

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J.-P., Stahl, K., Prudhomme, C., et al. (2017). The European 2015 drought from a hydrological perspective. *Hydrology and Earth System Sciences*, *21*(6), 3001–3024. https://doi.org/10.5194/hess-21-3001-2017

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, *13*(3), 245–259.

Maraun, D. (2013). When will trends in European mean and heavy daily precipitation emerge? *Environmental Research Letters*, *8*(1), 14004. https://doi.org/10.1088/1748-9326/8/1/014004

Ministère de l'Ecologie du Développement durable et de l'Energie (2019). HYDRO. http://www.hydro.eaufrance.fr/

Mohan, S., & Sahoo, P. K. (2008). Stochastic simulation of droughts. Part 1: Point droughts. *Hydrological Processes*, *22*, 854–862. https://doi.org/10.1002/hyp

Parry, S., Hannaford, J., Lloyd-Hughes, B., & Prudhomme, C. (2012). Multi-year droughts in Europe: Analysis of development and causes. *Hydrology Research*, *43*(5), 689. https://doi.org/10.2166/nh.2012.024

Parry, S., Wilby, L. R., Prudhomme, C., & Wood, J. P. (2016). A systematic assessment of drought termination in the United Kingdom. *Hydrology and Earth System Sciences*, *20*(10), 4265–4281. https://doi.org/10.5194/hess-20-4265-2016

Parsons, L. A., LeRoy, S., Overpeck, J. T., Bush, M., Cárdenes-Sandí, G. M., & Saleska, S. (2018). The threat of multi-year drought in Western Amazonia. *Water Resources Research*, *54*, 5890–5904. https://doi.org/10.1029/2017WR021788

Radziejewski, M., Bardossy, A., & Kundzewicz, Z. (2000). Detection of change in river flow using phase randomization. *Hydrological Sciences Journal*, *45*(4), 547–558. https://doi.org/10.1080/02626660009492356

Rizzi, J., Nilsen, I. B., Stagge, J. H., Gisnås, K., & Tallaksen, L. M. (2017). Five decades of warming: Impacts on snow cover in Norway. *Hydrology Research*, *49*(3), 670–688. https://doi.org/10.2166/nh.2017.051

Salas, JD, & Lee, T. (2010). Nonparametric simulation of single-site seasonal streamflows. *Journal of Hydrologic Engineering*, *15*(4), 284–296. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000189

Sarailidis, G., Vasiliades, L., & Loukas, A. (2019). Analysis of streamflow droughts using fixed and variable thresholds. *Hydrological Processes*, *33*(3), 414–431. https://doi.org/10.1002/hyp.13336

Schneider, C., Laizé, C. L. R., Acreman, M. C., & Flörke, M. (2013). How will climate change modify river flow regimes in Europe?. *Hydrology and Earth System Sciences*, *17*(1), 325–339. https://doi.org/10.5194/hess-17-325-2013

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.2307/2285891

Sharma, A., Tarboton, D. G., & Lall, U. (1997). Streamflow simulation: A nonparametric approach. *Water Resources Research*, *33*(2), 291–308.

Smakhtin, V. Y., Sami, K., & Hughes, D. A. (1998). Evaluating the performance of a deterministic daily rainfall-runoff model in a low-flow context. *Hydrological Processes*, *12*(5), 797–811.

Spinoni, J., Naumann, G., Vogt, J. V., & Barbosa, P. (2015). The biggest drought events in Europe from 1950 to 2012. *Journal of Hydrology: Regional Studies*, *3*, 509–524. https://doi.org/10.1016/j.ejrh.2015.01.001

Stagl, J. C., & Hattermann, F. F. (2015). Impacts of climate change on the hydrological regime of the Danube river and its tributaries using an ensemble of climate scenarios. *Water*, *7*(11), 6139–6172. https://doi.org/10.3390/w7116139

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., Van Lanen, H. A. J., Sauquet, E., et al. (2010). Streamflow trends in Europe: Evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, *14*(12), 2367–2382. https://doi.org/10.5194/hess-14-2367-2010

Stahl, K., Tallaksen, L. M., Hannaford, J., & Van Lanen, H. A. J. (2012). Filling the white space on maps of European runoff trends: Estimates from a multi-model ensemble. *Hydrology and Earth System Sciences*, *16*(7), 2035–2047. https://doi.org/10.5194/hess-16-2035-2012

Staudinger, M., Stahl, K., & Seibert, J. (2014). A drought index accounting for snow. *Water Resources Research*, *50*, 7861–7872. https://doi.org/10.1002/2013WR015143

Tallaksen, L. M., & Hisdal, H. (1997). Regional analysis of extreme streamflow drought duration and deficit volume. *Friend'97 - Regional Hydrology: Concepts and Models for Sustainable Water Resource Management*, *246*, 141–150. https://doi.org/10.1212/WNL.0b013e31823ed0a4

Tallaksen, L. M., Madsen, H., & Clausen, B. (1997). On the definition and modelling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal*, *42*(1), 15–33. https://doi.org/10.1080/02626669709492003

Tallaksen, L. M., & van Lanen, H. A. J. (2004). *Hydrological drought. Processes and estimation methods for streamflow and groundwater*, vol. 48. Amsterdam: Elsevier. https://doi.org/10.1007/978-94-015-9472-1

Van Loon, A. F. (2015). Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Van Loon, A. F., & Laaha, G. (2015). Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*, *526*, 3–14. https://doi.org/10.1016/j.jhydrol.2014.10.059

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, *43*, 1–13. https://doi.org/10.1029/2006WR005653

Wijayaratne, L. H., & Golub, E. (1991). Multiyear drought simulation. *JAWRA Journal of the American Water Resources Association*, *27*(3), 387–395. https://doi.org/10.1111/j.1752-1688.1991.tb01438.x

Wong, W. K., Beldring, S., Engen-Skaugen, T., Haddeland, I., & Hisdal, H. (2011). Climate change effects on spatiotemporal patterns of hydroclimatological summer droughts in Norway. *Journal of Hydrometeorology*, *12*(6), 1205–1220. https://doi.org/10.1175/2011jhm1357.1

Yevjevich, V. (1967). An objective approach to definitions and investigations of continental hydrologic droughts (*Tech. Rep. No. August*). Boulder CO: Colorado State University.

Zekollari, H., Huss, M., & Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. *The Cryosphere*, *13*, 1125–1146. https://doi.org/10.5194/tc-13-1125-2019