Streamflow drought: implication of drought definitions and its application for drought forecasting

Samuel J. Sutanto[1] and Henny A. J. Van Lanen[1]

[1]Hydrology and Quantitative Water Management Group, Environmental Sciences Department, Wageningen University and Research, Droevendaalsesteeg 3a, 6708PB, Wageningen, the Netherlands

Correspondence: Samuel Sutanto (samuel.sutanto@wur.nl)

Abstract. Streamflow drought forecasting is a key element of contemporary Drought Early Warning Systems (DEWS). The term streamflow drought forecasting ~~, rather than streamflow forecasting~~(not streamflow forecasting), however, has created confusion within the scientific hydro-meteorological community, as well as in operational weather and water management services. Streamflow drought forecasting requires an additional step, which is the application of a drought identification method to the forecasted streamflow time series. The way, how streamflow drought is ~~defined~~identified, is the main reason for this misperception. The purpose of this study, therefore, is to provide a comprehensive overview of the differences ~~within~~ of streamflow droughts using different identification approaches for European rivers, including an analysis of both historical drought and implications ~~of forecastingof these extreme events~~for forecasting. Streamflow data were obtained from ~~a~~ the LISFLOOD hydrological model forced with gridded meteorological ~~observed~~ observations (known as LISFLOOD-Simulation Forced with Observed, SFO). The same model fed with seasonal meteorological forecasts of the European Centre for Medium-range Weather Forecasts system 5 (ECMWF SEAS 5) was used to obtain the forecasted streamflow. Streamflow droughts were analyzed using the ~~Variable Threshold (VT), Fixed Threshold (FT~~daily and monthly Variable Threshold methods (VTD and VTM), daily and monthly Fixed Threshold methods (FTD and FTM), and the Standardized Streamflow Index (SSI). Our results clearly show that streamflow droughts derived from different approaches deviate from each other ~~both in occurrence and timing, associated with~~ in their characteristics, which also vary in different climate regions across Europe. The ~~occurrence of FT drought~~ daily threshold methods (FTD and VTD) identify 25-50% more drought events as the monthly threshold methods (FTM and VTM) and accordingly the average drought duration is longer for the monthly than for the daily threshold method. The fixed threshold methods (FTs, FTD, and FTM), in general, identify earlier drought than the variable threshold methods (VTs, VTD, and VTM). In addition, the droughts obtained with monthly identification approaches also have higher drought deficit volumes (about 25-30%) than the daily approaches. Overall, the characteristics of SSI-1 drought are more or less similar to what is being identified by the monthly threshold approaches (FTM and VTM). The different outcome obtained with the drought identification methods illustrated with the historical analysis is also found in drought forecasting, as documented for the 2003 drought across Europe and for the Rhine River specifically. To the end, there is ~~higher than droughts based upon VT and SSI, which highlights the importance of seasonality. FT drought happens earlier in the year than droughts obtained from VT and SSI. The use of aggregating daily streamflow data into monthly time windows for forecasting drought , such as the application of 30-day Moving Average (30DMA) , is recommended to identify the VT and FT droughts. This approach will~~

~~eliminate the undesired minor drought events, which are identified when using non-aggregated daily flow data. There is~~ no unique hydrological drought definition (identification method) that fits all purposes, hence developers of DEWS and end-users should clearly agree ~~among themselves~~ in the co-design phase upon a sharp definition on which type of streamflow drought is required to be forecasted for a specific application.

1 Introduction

Drought is a creeping natural disaster that has major socio-economic and environmental impacts across the world (e.g., Tallaksen and Van Lanen , 2004; Wilhite et al. , 2007; Ding et al., 2011; Van Dijk et al. , 2013; Stahl et al., 2016; Haile et al. , 2019). The IPCC (2014) reports with very high confidence that impacts from among others drought on society are already considerable. Drought hazard and ~~its~~ their impacts are projected to increase in numerous regions under a future warmer climate (e.g., Feyen and Dankers , 2009; Forzieri et al., 2014; Prudhomme et al., 2014; Wanders et al. , 2015; Samaniego et al., 2018). Gu et al. (2020) analyzed how drought influences regional gross domestic product (GDP) under different representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) at the global scale. The fraction of drought-affected GDP relative to the country's GDP would equal 100% in over about 75 countries under 1.5°C warming, which is projected to increase to over 90 countries under 2.0°C warming. There is an urgent necessity for society to respond to these signs. National ~~drought policy plans~~ Drought Policy Plans (NDPPs) should be implemented that convert the usually reactive drought ~~crises~~ crisis management into a pro-active risk management (Sivakumar et al., 2014; WMO and GWP , 2014; Poljanšek et al., 2017). One of the elements to be included in the NDPP is a Drought Early Warning System (DEWS) that in addition to real-time monitoring contains operational drought forecasting with appropriate lead times (i.e. multi-months or seasonal).

The term drought forecasting has been used in an indefinite way, which has created misconceptions, miss-citations, and confusion in the scientific hydro-meteorological community (authors, readers, editors, and reviewers), as well as among policy makers, and in operational weather and water management services. An explicit definition of what is being forecasted is crucial to avoid any misunderstanding on the usability of drought forecast products for different purposes. Firstly, meteorological drought forecast systems have been developed (e.g., Mishra and Desai , 2005; Belayneh et al., 2014; Dutra et al., 2014), which frequently use the Standardized Precipitation Index, SPI (McKee et al., 1993), or the Standardized Precipitation Evaporation Index, SPEI (Vicente-Serrano et al., 2010). These aggregate precipitation (SPI), and precipitation minus potential evaporation (SPEI) over at least one month and have lead times of one to several months. ~~Conventional~~ It should be noted that conventional weather forecast systems~~that~~ , which predict low or no precipitation and above normal temperature, as part of their regular suite of forecast products, should be not classified as a drought forecasting system, because of their rather short lead time (sub-daily to 10-15 days). Secondly, hydrological drought forecasts are provided (e.g., Pozzi et al., 2013; Sutanto et al., 2020a), which involve groundwater, river flow, soil moisture, and runoff. Hydrological drought deviates from meteorological drought (e.g., Changnon , 1987; Peters et al., 2003; Mishra and Singh, 2010; van Loon and van Lanen , 2012; Barker et al., 2016; Sutanto et al., 2020b), which means that the latter cannot straightforwardly be used to predict drought in groundwater or river flow. Because of all these differences, an explicit delineation of what is being forecasted is a prerequisite. Here, our study focuses on ~~hydrological~~ streamflow drought forecasting, ~~specifically of drought in the river (streamflow drought)~~as part of hydrological drought forecasting, which is defined as below-normal streamflow (Hisdal et al. , 2004; Peters et al., 2006; Fleig et al., 2006; Feyen and Dankers , 2009; Sarailidis et al., 2019).

Forecasting of streamflow drought follows different approaches on how the hydrological drought is defined (Hisdal et al. , 2004; van Loon , 2015), which is also essential to consider when using forecast products. Yuan et al. (2017) use the so-called standardized approach. They ~~calculated~~ forecasted the Standardized Streamflow Index (SSI), which measures monthly normalized anomalies in streamflow and, if negative, then SSI signifies a dry anomaly. Others applied the threshold approach to ~~derive~~ predict drought in river flow from the forecasted flow time series. This implies that the river is in drought when it is below a predefined flow. Marx et al. (2018) and Wanders et al. (2019) use a fixed threshold meaning that it does not vary throughout the year. Usually, a percentile of the flow duration curve is taken using all flow data to identify the fixed threshold. ~~In~~ On the contrary, Fundel et al. (2013), Sutanto et al. (2020a), and van Hateren et al. (2019) have used the variable threshold approach to identify drought events with their hydrological drought forecasting system. In this approach, the threshold varies over the year and accounts for seasonality, which means that forecasted drought can occur in every season. The threshold is derived from, for instance, the daily, monthly, or seasonal flow duration curve.

In the context of this study, it is also important to ~~realize~~note, that hydrological drought forecasting is different from just streamflow forecasting (e.g., Day , 1985; Clark and Hay , 2004; Schaake et al., 2007; Bell et al., 2017; Mendoza et al., 2017; Arnal et al., 2018; Duan et al., 2019), although the latter provides key input data to derive hydrological drought. For hydrological drought forecasting, an additional step ~~is required~~has to be taken, that is, derivation of drought events from the forecasted flow time series, e.g. the flow time series is converted ~~in~~ into a time series of drought events. In summary, the different approaches that are being used to identify and communicate drought in rivers call for an explicit description of what is being meant. Clearly, different users have diverse needs and these can be accommodated by forecasts of drought indices obtained by different identification approaches as provided in the DEWS.

The purpose of this study, therefore, is firstly to provide a clear overview of the differences between streamflow drought using different definitions ~~.~~ (i.e. identification methods) and temporal resolutions, i.e. daily and monthly. This is done through a historic analysis using data from 1990-2018. Differences are illustrated for ~~the entire Europe~~ entire Europe to investigate spatial aspects and some major rivers across different climate regions to study temporal aspects. The historical analysis is innovative because it covers the entire pan-European river network with all its hydrological regimes instead of a single country (Heudorfer and Stahl , 2017; Vidal et al. , 2010) or a river basin (Sarailidis et al., 2019) and involves both threshold and standardized identification approaches ~~. Eventually,~~ (drought indices), incl. different temporal resolutions. Secondly, in this study, its implications for forecasting hydrological drought are elaborated using the extreme 2003 drought in Europa as an example, which demonstrates that ~~there no one fits all~~ none of the hydrological drought forecast ~~. The~~ approaches fits all needs.

The paper is organized as follows: the datasets with observed and ensemble forecasts of streamflow~~datasets~~, used in this study, are described in Section 2.1, followed by a description of the methodology to derive the drought indices, i.e. drought identification approaches (Section 2.2), an explanation of presented characteristics, such as the number of drought occurrences (frequency), timing, duration, and deficit volume (Section 2.3). The results are presented and discussed in Section 3. We divided the result section into two parts, that are, drought characteristics analysis using different identification approaches for 1) historical data, and 2) forecasted data of the 2003 drought. Detailed analysis of drought characteristics for both historic and forecasts is provided for the selected river basins. Finally, we conclude the findings in Section 4.

2 Data and Methods

2.1 Data

A state-of-the-art hydrological model, LISFLOOD, was used to simulate the streamflow of rivers across Europe from 1990 to 2018, which was derived from the routed runoff of 5 x 5 km grid cells (van der Knijff et al., 2010; Burek et al., 2013a). We decided to use simulated river flow rather than the observed flow, because sufficiently-long ~~times~~ time series of observed flow for a common period covering the whole of ~~Europe~~ the European river network do not exist. The LISFLOOD model was fed by gridded meteorological observations (e.g. ~~,~~ precipitation, temperature, relative humidity, wind speed) to obtain daily ~~proxy~~ proxies for observed streamflow data, known as LISFLOOD-Simulation Forced with Observed (SFO). The gridded meteorological observation data were collected from ground observations (>5000 synoptic stations), obtained from the Joint Research Center (JRC) meteorological database, the Global Telecommunication System of the WMO, and high-resolution data received from the National ~~member~~ Member States institutions (Pappenberger et al., 2011). The time series of proxy observed streamflow data for each cell at the river network (river grid cell) across Europe were used to derive the streamflow drought following different approaches. Potential evapotranspiration was calculated through the offline LISVAP pre-processor based on the Penman-Monteith equation (van der Knijff, 2008; Burek et al., 2013b). A kinematic wave approach was used for routing the water movement on the river network.

The model was calibrated using time series of observed river streamflow from over 700 calibration stations across Europe. The hydrological skill of the LISFLOOD model expressed by the Kling-Gupta Efficiency (KGE) shows that 42% of all calibration stations score a KGE higher ~~that~~ than 0.75, 33% of all stations score a KGE between 0.5 and 0.75, and 25% of all stations score a KGE below 0.5 (Arnal et al., 2019). Although the model was originally developed for operational flood forecasts in the EU under the European Flood Awareness System (EFAS) platform (Thielen et al., 2009; Pappenberger et al., 2011; Cloke et al., 2013), the LISFLOOD model has been tested for drought identification, forecasting and projections (Feyen and Dankers , 2009; Trambauer et al., 2013; Forzieri et al., 2014; Sutanto et al., 2019, 2020a, b; van Hateren et al., 2019). It appears from these studies that the model also performs rather well for drought studies. The model used in this study is the latest version of LISFLOOD that has been implemented in the operational EFAS since 2019 (version 3).

Besides the SFO data, we also used re-forecasted (known as hindcast) time series of streamflow data for the year 2003, as an example of drought forecasts. The European Centre for Medium-range Weather Forecasts System 5 (ECMWF S5) seasonal forecast was used as forcing for the LISFLOOD hydrological model to forecast streamflow at the pan-European scale (Stockdale et al., 2018). The seasonal forecasts are available as daily re-forecast data for each month from day 1 to day 215 (7 months lead-time) for 25 ensemble members ~~(see Sutanto et al. (2020a) for detailed information)~~(see Sutanto et al., 2020a, for detailed information . In this study, we selected the re-forecast data from 2003, because a severe drought across extended areas in Europe was observed (Fink et al., 2006; Ionita et al. , 2017; Laaha et al., 2017).

2.2 Streamflow drought identification

In this study, we employed two well-known drought identification methods, i.e. the threshold drought approach and the standardized drought approach (van Loon , 2015). ~~Firstly~~

2.2.1 The variable and fixed threshold methods

Using both the variable and fixed threshold-based approaches, drought was derived from time series of streamflow data from 1990 to 2018 and re-forecasted data of 2003 ~~using the threshold-based approaches to indicate~~ to calculate the water deficit in different domains of the water cycle, in our case, it is the ~~surface water domain, i.e. determination of~~ streamflow deficit. ~~This~~ The threshold approach originates from the theory of runs and is developed based on a pre-defined ~~variable~~ threshold level (Yevjevich , 1967; Hisdal et al. , 2004). The threshold approach uses an event-based sampling of the flow time series to convert this into a time series of drought events. The drought event starts when the hydrological variable falls below the threshold value and ends when it equals or rises above the threshold value. In this study, we applied two different types of drought threshold approaches, which are the ~~Fixed Threshold (FT~~ Variable Threshold (VT drought) and the ~~Variable Threshold (VT drought) .~~ Fixed Threshold (FT drought) on both daily (VTD and FTD) and monthly streamflow data (VTM and FTM). The latter was done to allow a comparison of the VTM and FTM approaches with the Standardized Streamflow Index (SSI, Nalbantis and Tsakiris , 2009; Vicente-Serrano et al., 2012), which uses a monthly temporal resolution. However, the use of threshold approaches on monthly streamflow data to identify monthly drought is not common practice (e.g., Fleig et al., 2006; Peters et al . To the author's knowledge, only a few studies used monthly data (e.g., Tallaksen et al. , 2009; van Loon et al. , 2019) to derive drought using the threshold method, and this was done only for scientific purposes.

FT uses a pre-defined threshold, which is constant over the year and unique for each river grid cell. The ~~VT varies in each day~~pre-defined VT varies for each day/month and for each river grid cell. The VT method gains more popularity because this method considers ~~streamflow seasonality in the dataset (Hannaford et al. , 2011; Prudhomme et al., 2011; van Loon , 2015).~~ seasonality in streamflow (Hannaford et al. , 2011; Prudhomme et al., 2011; van Loon , 2015). For the VT and FT thresholds, we calculated the threshold values using 29 years of monthly streamflow data that were obtained by aggregating daily flow data. Thresholds in this study were derived from the ~~90~~80^{th} percentile of the streamflow (~~Q90~~Q80, flow duration curve), which are the flows that are equaled or exceeded ~~90~~ 80 percent of the time. The ~~Q90~~ Q80 was considered as the drought threshold because most of the rivers across Europe are classified as perennial rivers. Moreover, the ~~Q90~~ Q80 threshold lays within the range of the 70^{th}-90^{th} percentile that is commonly used in drought studies (Tallaksen et al. , 1997; Hisdal et al. , 2004; Fleig et al., 2006; Wong et al. , 2011). Using the ~~Q90,~~ Q80 means that fewer drought events are identified compared with higher thresholds, e.g. ~~,~~ Q70~~and Q80.~~

~~A backward~~ . For the VTM method, the calculated 12 monthly thresholds could be straightforwardly be used in the drought analysis, whereas for the VTD method, the calculated monthly thresholds were firstly assigned as the threshold levels for each day of the respective months. This resulted in a jump between two consecutive months, which showed unrealistic drought behavior. Therefore, as a second step, a 30-day centered moving average (30DMA) ~~method was employed to the~~ smoothing technique was applied to the monthly thresholds, eventually leading to daily thresholds (365 and 366 thresholds for no leap and leap years, respectively) (van Loon et al. , 2012; van Lanen et al., 2013; Beyene et al., 2014). For the FTM and FTD method, we used the same threshold, which is constant throughout the year by definition. In the drought analysis, the same threshold values are applied every year from 1990 to 2018.

The centered 30DMA method was also employed in the historical daily streamflow data ~~as well as to the VT threshold to~~ to reduce the number of minor droughts (pooling procedure) (Fleig et al., 2006; van Loon and van Lanen , 2012; Sarailidis et al., 2019). This means that we ~~were moving~~ averaged the first 30 days of the SFO data (from 1 to 30 January 1990) to calculate the streamflow on ~~30~~ 16 January 1990. For ~~the~~ 31 January 1990, we ~~were moving~~ averaged the SFO data from ~~2~~ 16 January 1990 to ~~31 January~~ 14 February 1990 and so on until ~~31~~ 15 December 2018. Missing 30DMA streamflow data from 1 to ~~29~~ 14 January 1990 and from 16 to 31 December 2018 were not relevant since we have started drought analyses from the hydrologic year 1991 (from October 1990 to September 1991) to the hydrologic year 2018 (from October 2017 to September 2018). We applied the same hydrologic year for all European rivers. The reason for choosing the same hydrologic year (in our case: 28 years) is to ensure consistency in the analysis at the European level. ~~For the threshold, we calculated the daily threshold values using the original streamflow data without applying~~

We also applied the centered 30DMA ~~for each day (365 and 366 thresholds for no leap and leap years, respectively). The threshold values are the same for every year from 1990~~ to ~~2018. We then applied the backward 30DMA method to these daily threshold values and simply neglected the first 30 days threshold (1 to 29 January 1990) for the same reason as above. We also applied 30DMA to the~~ the forecast data. To handle the forecast streamflow data at the start of the ~~215 day~~ 215-day forecasts, we ~~moving averaged 29~~ averaged 15 days of preceding observed data (SFO) with ~~one day of~~ 15 days of the forecast to predict a possible drought event on the first day. For the second forecast day, we ~~moving averaged 28~~ averaged 14 days of preceding observed with ~~two~~ 16 days of forecast and so on. For example, the 30DMA forecasted streamflow on 1 ~~st~~ August 2003 was obtained from moving averaging the SFO data from ~~3~~ 17 July to 31 July 2003 with the forecasted streamflow ~~on the first day (~~from 1 August to 15 August 2003 (to predict a possible drought on 1 August 2003, lead time one day). Hence, the first ~~29~~ 15 forecasted streamflow data from the ~~215 day time series include~~ 215-day time series included some observed flow ~~.~~ that increases drought forecast skill for the first 15 days, which will affect possible forecasted drought events at the start of the forecast record using the VTD and FTD. The fusion method was applied to each of the 25 forecast ensemble members. The 30DMA method had not been applied to the monthly streamflow data for both historic period and forecasts. Thus, there is no influence of the SFO data on the monthly drought forecast analysis using the VTM and FTM.

~~Secondly, the~~

2.2.2 The standardized streamflow index

The Standardized Streamflow Index (SSI, Nalbantis and Tsakiris , 2009; Vicente-Serrano et al., 2012) was used to indicate also used to identify drought in the river. The SSI was calculated using the same theoretical background as the Standardized Precipitation Index (SPI, McKee et al., 1993). The SSI calculation for any river grid cell was based on a monthly average the monthly streamflow record that is fitted to a gamma distribution, which is then transformed into a normal distribution so that the expected median SSI for the site and desired period is zero. Please keep in mind that the 30DMA method was not applied for SSI analysis since SSI uses monthly average streamflow data. We decided to use the widely selected gamma distribution as general distribution for the whole Europe since it can be used for hydrological forecasting of both high and low flows (Slater and Villarini , 2018)and none of single distributions . Moreover, none single probability distribution would fit all streamflow time-series across Europe (Vicente-Serrano et al., 2012). A 6-month , in particular, it does not fit all monthly streamflow data in all river grid cells (n= 29,000). For example, sample properties of streamflow in January might differ from those in August in each of the river grid cells (Tijdeman et al., 2020). In summary, we obtained a gamma distribution parameter set for each river grid cell and month (in total > 348,000 sets).

A 1-month accumulation period was used in this study to avoid many minor drought events (SSI-6 drought), following studies from Trambauer et al. (2015) and Barker et al. (2016).SSI with 1-month (SSI-1 drought). Longer accumulation periods, e.g. SSI with 6-month accumulation period (SSI-1 drought)was added only for comparison with SSI-6 to prove the aforementioned reason (Fig.5 and Appendix Figures) SSI-6), as it was used in Trambauer et al. (2015) and Barker et al. (2016), was not selected in our study, since streamflow already comprises some catchment memory aspects (delayed flow from groundwater). Nevertheless, we need to realize that anomalies in the accumulated flow over a longer period (e.g. SSI-6) have relevance for some purposes, such as the management of surface water reservoirs. Negative SSI values indicate a drought event, which means that the streamflow in a certain month (accumulation of average streamflow data for six months for SSI-6, incl. five preceding months) is lower than the median streamflow of that month(median accumulation of average streamflow data for six months for SSI-6) and vice versa for positive SSIvalues. To forecast the SSI-6 . Four SSI classes are commonly distinguished, which are: 1) mild drought: $0>SSI\geq-1$, 2) moderate drought: $-1>SSI\geq-1.5$, 3) severe drought: $-1.5>SSI\geq-2$, and 4) extreme drought: $SSI<-2$ (Nalbantis and Tsakiris , 2009). In this study, however, we assumed the drought event to start when the SSI-1 falls below -0.84. The use of a threshold -0.84 for SSI warrants a fair comparison between the threshold approaches (Q80) and SSI-1 ($SSI<-0.84$) (Tijdeman et al., 2020). The above-mentioned gamma distribution parameter sets for SSI-1 and the threshold of -0.84 were used to identify drought events in the historic period (1990-2018) in each of the river grid cells of the pan-European river network.

To forecast a possible SSI-1 drought for a lead-time (LT) of x-month (x = 1, 2, ... ,7 months), we combined SFO data with forecast data, as introduced by ? and Dutra et al. (2014). also used the above-mentioned gamma distribution parameters sets. The SSI-1 times series were derived from the forecasted streamflow using these parameter sets (Sutanto et al., 2020a). For example, the forecasted SSI-6 for August to forecast SSI-1 using forecasted streamflow initiated on January 2003 with 1-month a lead-time (forecasts issued on of 7-month, we calculate the SSI-1 for January (LT=1), February (LT=2nd August 2003)was estimated by combining the SFO data from March to July2003 (five months)with August 2003 forecast data (one month)), up to July (LT=7) using the parameter sets from January, February, up to July, respectively. Same parameter sets were applied to each ensemble member to calculate 25 ensembles of SSI-1. To forecast the SSI-6 for September

2.3 Drought characteristics

Drought analysis using the threshold methods and the standardized approach shares several common major drought properties or characteristics, which are the number of drought occurrences/frequency (N), drought initiation time or timing (T), and drought duration (D). Another drought characteristics, namely drought deficit volume (DV), can be obtained only by using the threshold methods. The standardized approaches cannot be used to calculate the deficit volume, because it only provides information on the drought severity class (Section 2.2.2) and not about the amount of water that is not available during a drought event (m^3 in our case for streamflow). In this study, the number of drought occurrences, timing, duration, and deficit volume will be calculated using the threshold methods (VTD, FTD, VTM, and FTM). For the SSI-1 the same characteristics will be determined, except the deficit volume.

The number of drought occurrences (N) shows how many drought events occurred: 1) from October 1990 to September 2018 (hydrologic years), and 2) from the starting date of the forecast up to 215 days (7 months) ahead. The timing (T) for drought was determined based on the starting month of each drought event (1: Jan, 2: Feb,. . . , 12: Dec) in the time series either in the 28 years (historic analysis) or in the median of the ensembles of 215 days (7 months). If there is more than one drought event in the time series, which is common for the historic data, then we select the timing based on the starting month with the highest frequency. If there is more than two starting months with the same frequency, then we calculate the median value from the selected timings. For example, the month August is selected as drought timing, if months March, August, and October have the same frequency. If there are two starting months detected with the same frequency, then we chose the first timing. Drought duration, expressed in day for VTD and FTD and month for VTM and FTM, is the number of day/month when the streamflow or SSI is continuously below the threshold. If there is more than one drought event, then we average the duration of the events. The drought deficit volume (only threshold methods) is calculated by summing up the difference between streamflow and the threshold level per day/month over the drought event, expressed in m^3. For total drought deficit volume, we simply sum up deficit volumes from all drought events (either historic period or forecast period). Obviously, the average deficit volume in a river grid cell, which we use in the historic analysis, equals the total deficit divided by the number of droughts. In case of an ongoing drought in the forecast, e.g. a drought that already started prior to the forecast initiation, we determine the drought characteristics from the first day of the forecast. We do not consider what happened before. In case a drought still has not ended by the end of the forecast period (at day 215 or month 7), we break the drought event by the end of the forecast, meaning that we do not take into account the characteristics of the drought event beyond the forecast period. In addition, we also provide a maximum number of ensemble members indicating drought (Ne) for each forecast initiation as a percentage. For example, for forecasts initiated in July 2003 with 2-month lead-time (forecasts issued on with LT=7 month (from July 2003 to January 2004), we calculate Ne for every LT (1, 2nd August 2003), we combined the SFO data from April to July 2003 (four months) with forecast data for August and September 2003 (two months), and so on for the rest. The drought event was categorized into

~~four classes, which are: (i) mild drought : 0>SSI≥-1, (ii) moderate drought : -1>SSI≥-1.5, (iii) severe drought : -1.5>SSI ≥-2, and (iv)extreme drought : SSI<-2 (Nalbantis and Tsakiris , 2009).Similar to the threshold approach, the standardized method uses an event-based sampling of the flow time series to convert this into a time series of drought events for further analysis.~~ . . . ,7 months), and provide information only for the maximum number of Ne.

2.4 Köppen-Geiger climate classification

The Köppen-Geiger climate classification has been built based on observed global temperature and precipitation data ~~(Peel et al., 2007)~~ used in Peel et al. (2007). There are four main climate types found in Europe, which are cold (D), arid (B), temperate (C), and polar (E). Each climate type can be classified into several sub-climate types. In our study area, the dominant sub-climate types are Bsk, Csa, Cfa, Cfb, Csb, Dfc, Dfb, Dsa, Dfa, Dsc, and ET (Fig. ~~1).~~ **??**). Six sub-climate types are considered in the streamflow drought analysis across entire Europe, that is, the tundra climate (ET), the, warm-summer, humid continental climate (Dfb), the subarctic climate (Dfc), the temperate, oceanic climate (Cfb), the cold, semi-arid climate (Bsk), and the hot summer Mediterranean climate (Csa). The latter two types are clustered in the Mediterranean climate (Med). This means five climate regions that cover over 90% of the European area. In addition to the analysis of streamflow drought in all grid cells of the pan-European river network, four different rivers located in the major climate regimes of Europe were selected~~(Cfb, temperate oceanic climate; Dfb, warm-summer humid continental climate; Dfc, subarctic climate; and (Bsk, Mediterranean climate)~~. The locations of the selected rivers are as follow: 1) Rhine River near Cologne, Germany, located at 50.9°N and 6.9°E (Cfb), 2) Danube River near Budapest, Hungary, located at 46.9~~º~~°N and 18.9°E (Dfb), 3) ~~Kemijoki River near Kemi, Finland, located at 65.8~~Vuoksi River close to the Finnish-Russian border, located at 61.1°N and ~~24.6~~28.8°E (Dfc), and 4) Ebro River near Asco, Spain, located at 41.2°N and 0.6°E (Bsk). The four rivers are indicated by red dots in Figure ~~1.~~ **??**. For detailed information about climate classifications used in the study, see the Köppen-Geiger climate classification presented in Peel et al. (2007).

3 Results and discussion

We present the differences of streamflow droughts identified using different ~~definitions~~ drought identification approaches in two parts. The first part provides results and ~~discussion of~~ discusses the historical analysis that consists of the investigation of differences between drought analyzed using different approaches (i.e. drought definitions), in terms of ~~occurrences and timing in~~ drought characteristics both in over 29,000 river grid cells at the pan European scale, and four selected river basins in more detail (Section 3.1). The second part elaborates ~~an example of~~ the implication of streamflow drought ~~forecasts~~ forecasting using different definitions at the pan European scale and in one of the selected river ~~basin~~ basins (Section 3.2).

3.1 Historic analysis

3.1.1 Streamflow drought ~~occurrences~~characteristics across Europe

One of the most profound differences among streamflow ~~drought using different indices~~ droughts using different identification approaches is the occurrence of these events. ~~Based on the definition~~In a river grid cell, streamflow drought may be absent, ~~or occur onceor more~~ occur once, or even more than once in a hydrological year ~~in a certain river grid cell~~throughout the period 1990-2018. This happens when the streamflow falls below the ~~thresholds (VT and FT) or when it is lower than median streamflow (SSI). Streamflow drought might occur every year (28 events~~ threshold, which is Q80 (VTs and FTs) or equal to SSI<-0.84 in our study.

The largest deviation between drought occurrences obtained with the five different identification approaches is due to the temporal resolution. In entire Europe, the variable threshold using daily data (VTD) detects almost 50% more drought events than when applying monthly data (VTM), i.e. 49.6 and 26.6 events, respectively (Table **??** and **??**). The spatial distribution also shows this clearly (Fig. **??**a and **??**c). The deviation between the daily and monthly resolution for the whole of Europe is smaller (about 25%) ~~, but this is rare, as shown in Figure 2a (VT). In some regions, especially in cold regions, such as in northern Europe and Alps, the occurrence of VT droughts exceeds 28 events during the study period. However, in most river grid cells across Europe (96%of all river grid cells) , occurrence of VT drought is less than 28 events~~when fixed threshold approaches are applied (FTD: 39.6 and FTM: 28.6 events), see also Fig. **??**b and **??**d. The data also show that when a daily resolution is used, the VTD method identifies about 25% more events than the FTD method (Table **??**, Fig. **??**a, and **??**b), whereas deviations are small at the monthly scale (VTM versus FTM, Table **??**, Fig. **??**c, and **??**d). ~~The number of FT drought is in general higher than of VT droughts. In more than 50% of all river grid cells, the frequency of FT drought is higher than VT drought, which especially applies to the cold regions (Fig. 2b). In these cold regions, drought occurs not only during summer or autumn due to below-normal precipitation and higher evapotranspiration, but also during winter and spring seasons, depending on the length of the frost period and the timing of the snow incident, accumulation and melting (cold snow season drought)(van Lanen et al., 2004; Pfister et al., 2006; van Loon and van Lanen , 2012). A warm snow season drought may also occur during spring or summer, associated with no snow occurrence during winter or earlier snowmelt than normal (van Lanen et al., 2004; van Loon et al. , 2010). This causes an early peak in streamflow, resulting in lower streamflow in late spring and summer. van Loon and van Lanen (2012) discuss in detail these types of drought events. In general, the number of SSI-6 drought is similar to VT, i. e. in 91% of all grid cellsthe occurrence is lower than 28 events.~~ At the pan-European scale, there are no substantial differences between drought occurrences (<15%) derived with the methods using monthly data (VTM, FTM and SSI-1, Table **??**, Fig. **??**c, **??**d, and **??**e).

~~VT and FT droughts also occurred more than once a year in some rivers flowing from Spain to Portugal that might be caused by minor drought events~~ The maps (Fig. **??**a and **??**b) show that in about 20% (VTD approach) and 5% (FTD approach) of the pan-European river grid cells, streamflow drought on average occurs at least twice a year (>~~30 events, red color Fig. 2a and 2b). Minor drought events are also the main reason for high occurrence of FT droughts in the UK and west Europe(>30 events)~~60 events). However, in parts of Sweden and Finland, and southeast Europe, such as ~~France and Germany (Fig. 2b).~~

~~Here,~~ Romania, Serbia, and Bulgaria, the occurrence of VTD and FTD droughts does not exceed 30 events during the study period. The highest number of droughts is identified in the temperate oceanic climate (Cfb), whereas the lowest is found in the Mediterranean climate region (Med), irrespective of the ~~FT threshold is larger than the VT threshold in the dry season (summer), which causes a higher number of periods with streamflow falling below the threshold. For~~ identification approach. Clearly, a number of events vary amongst identification methods, for example, the ~~average VT threshold during summer in the Loire River France, close to Angers city, is 145 m^3/s, which is lower than the FT threshold (219 m^3/s). The higher occurrence of FT droughts in the regions' border with west Russia is also caused by minor drought events that occur during winter. In this season, the VT threshold, e.g. in the Daugava River in Minsk (81 m^3/s), is lower than in summer due to lower streamflow during cold period in winter (112 m^3/s). A different number of drought occurrences between VT and SSI-6 is clearly seen in Ireland~~ range for the Cfb and Med climates is 30.4-57.8 and 22.6-41.0 events, respectively (Table **??** and **??**).

Minor drought events are assumed to be the main reason for the high occurrence of VTD and FTD droughts in the major European rivers (>60 events), compared to VTM and FTM droughts (Fig. ~~2a and 2c, 100% and 65% of all Irish river grid cells have less than 28 events, respectively). In this region, the number of SSI-6 drought events is similar to FT drought, which is in some cases more~~ **??**a, **??**b, **??**c, and **??**d). To prove our hypothesis, we plotted the percentage of VTD drought events that have duration of shorter than 30 ~~events. SSI-1 (hydrological drought index if only one month of accumulation is considered)~~days (Fig. **??**). Here, it can be seen that many rivers in the west and east Europe (Cfb and Dfb climates), as well as, the mountainous regions in Norway (Dfc and ET), ~~on the other hand, gives higher drought occurrence (~~experience lots of minor drought events (>~~55 events in Ireland) than other approaches (VT, FT, and SSI-6)as been shown in Figure A1 (Appendix). This is plausible due to the occurrence of more drought events when the monthly streamflow drops below the median monthly flow.~~

~~In this study, we highlight the occurrence of minor droughts derived with the threshold methods especially the FT method as a causative factor for high drought occurrence in certain regions. A high number of minor droughts with short duration and small deficit volume may disturb drought analysis. Tallaksen et al. (1997) and Fleig et al. (2006) suggest several pooling procedures to reduce the numberof minor droughts, such as applying the inter-event time method, the moving average procedure, and the sequent peak algorithm. In addition to these techniques, exclusion of drought event with duration shorter than a given number of days is recommended (Jakubowski and Radczuk , 2004; van Loon et al. , 2012). For example, van Loon et al. (2012) excluded drought that has duration less than three days. In this study, although we excluded many~~ 60% of total number, and even more, up to almost 100% in a few rivers indicated by red color). Mediterranean and Dfc climate regions (Sweden and Finland), in general, show a smaller number of minor drought events ~~by applying moving average procedures, which is the 30DMA for drought analyses (Section 2.2), a few minor drought events are still visible (short drought event). A clear example of the exclusion of minor drought events by using the 30DMA approach can be seen in Figure 4 that~~ (∼30% of total), meaning that drought events in these regions (Fig. **??**a) are caused by droughts that have a long duration. This will be discussed later ~~in the Section 3.1.3 and 3.1.4.~~ (Fig. **??**).

3.1.2 Timing of streamflow drought

To investigate the timing of streamflow drought, we present the month when drought mostly started starts in each grid cell of European rivers (Fig. 3??). The timing was determined for each drought event in the period October 1990 to September 2018 (coincides with hydrologic years in most of Europe). Figures 3a, 3b, and 3c indicate that 2018. Figure ?? indicates that, as expected, there is a strong relation between streamflow drought timing in the rivers and the Köppen-Geiger climate regions across Europe (Fig. 1). compare Fig. ?? and ??). This also differs among drought identification methods. In general, the fixed threshold methods (FTD and FTM) detect earlier drought (Table ?? and ??) than the fixed threshold methods (VTD and VTM), except in many rivers located in the humid continental climate (Dfb). Rivers located in cold climate regions Dfc and ET (subarctic climate and tundra climate, respectively(Dfb and Dfc), such as in northern Europe and northern and eastern Europe, and the Alps, experience early streamflow drought events in early winter for FT drought, and between late winter and early spring for VT drought and SSI-6. Rivers located in Dfb regions (warm-summer humid continental climate), such as in central and east Europe, have a broad range of timings from winter to summer, which means that we could not distinguish between droughtidentification approaches. The timing of drought for the remaining climate regions (Cfb : temperate oceanic climate, Csb: warm-summer Mediterranean climate, Csa: hot-summer Mediterranean climate, and Bsk: cold semi-arid climate) is in the summer for FT drought and later for VT drought(March-April) when the daily variable threshold method (VTD) is applied (Fig. ??a, Table ??), and later when monthly data (VTM) are used (May-July, Fig. ??c, Table ??). In addition to below normal precipitation and above normal evaporation (classical rainfall deficit drought), drought in cold regions also depends on the length of the frost period and the timing of snow incidents, accumulation, and melting (cold snow season drought) (van Lanen et al., 2004; Pfister et al., 2006; van Loon and van Lanen , 2012). A warm snow season drought may also occur during spring or summer, associated with no snow occurrence during winter or earlier snowmelt than normal (van Lanen et al., 2004; van Loon et al. , 2010). This causes an early peak in streamflow, resulting in lower streamflow in late spring and summer. In the warmer climates (Cfb and Med) droughts start later (mostly July-October) than in the colder regions. However, there is a difference between variable and fixed threshold approaches, i.e. around summer to early winter. In these climate regions, the distinction between FT drought (Fig. 3b) on one hand, and VT FT droughts largely begin earlier (July-August, Fig. ??b and ??d) than the VT droughts (September-October, Fig. ??a and ??b, Table ?? and ??). The start of SSI-1 drought in most climates is closest to VTM droughts (Fig. ??e, ??c, and ??d, Table ??).

The average duration of the droughts (Fig. 3a)and SSI-6 (Fig. 3c) droughts on the other hand is obvious. The timing for FT drought in these regions shows that drought occurs usually during summer. In 83% of all river grid cells in the Cfb, Csb, Csa and Bsk climates, ??) is negatively correlated with the number of droughts when using the threshold methods (Fig. ??). We have seen that applying methods using daily data result in more drought occurrences than those that use monthly data. Hence, the average drought duration of events is connected with the temporal resolution of the methods. We have seen that droughts obtained with methods fed by daily data (Fig. ??a and ??b) are shorter than those applying monthly data (Fig. ??c and ??d). For instance, for the whole pan-European river network, VTD droughts are about 60% shorter than VTM droughts (44.6 days and 2.4 months/73 days, respectively, Table ?? and ??). For the FT drought, the FT drought occurs in the monthsJune, July and August. However, if we take into account the seasonality, as in the VT and SSI-6 approaches, following average drought duration was found: FTD 56.0 days and FTM 2.5 months/74 days, implying that the FTD droughts are about 30% shorter than FTM events. We also observed that rivers in the Cfb climate have the highest number of droughts and those in the drought does not have to occur during the dry period. VT drought only starts to occur in the dry season when the river is low for a sustained period. VT and SSI-6 droughts appear mostly in autumn (Vidal et al. , 2010). On the other hand, the Standardized Streamflow Index with shorter accumulation period (SSI-1 drought) has earlier drought timing, which is in several grid cells in spring and summer (in 42% of all river grid cells, see Figure A2) .

Rivers flowing through different climate regions and associated seasonality are affected by different VT and SSI-6 drought timings, e.g. the Rhine River flowing from Switzerland, via Germany to the Netherlands (Fig. 3a Mediterranean climate region have the lowest number of droughts, implying that the average drought duration in the Cfb climate is shorter (36.4 and 3c). This causes amixing. Downstream, the Rhine River is located in the Cfb region 47.2 days, Table **??**, and 1.9 months/57 days, and 2.2 months/66 days, Table **??**) than in the Mediterranean region (56.3 and 68.4 days, Table **??**, and 2.9 months/87 days, and 2.7 months/81 days, Table **??**), see also Fig. **??**a, **??**b, **??**cs and **??**d. The average drought duration estimated with the SSI-1 approach is close to both the VTM and FTM methods (Fig. **??**c, **??**d, and **??**e). Differences in average drought duration amongst methods using monthly data for the whole of Europe are around 10% (Table **??**).

The average drought deficit volume that has been detected by the different drought identification methods is to some extent linked to the temporal resolution of the methods. For example, for the whole of Europe, we found higher average drought deficits with the approaches using monthly data (VTM: 1,371 and FTM: 1). In this climate, VT and SSI-6 droughts usually start by the end of summer to early winter (see neighboring rivers). However, our analysis shows that the VT and SSI-6 droughts in the downstream part mostly start before summer. Short drought events in winter/spring in the upstream part of the Rhine play an important role in drought timing in the downstream area (Fig. 3 around Alpine region,ET climate) . This also applies when SSI-6 is replaced with SSI-1 ,211 m^3) than those fed by daily data (VTD: 919 and FTD: 913 m^3), indicating about 25-30% higher drought deficit volumes (Table **??** and **??**). Plotting average drought deficit volume across European rivers (Fig. A2). The FT drought, on the other hands, has drought timing in the end of autumn (**??**), in general, shows higher deficit volumes for the bigger rivers in central and north Europe (except coastal areas), which is partly caused by not standardizing the deficit volumes. Hence, the analysis of the drought deficit volume using different identification approaches is more meaningful, if we summarize the results for each climate region (Table **??** and **??**) or for selected river grid cells (Section 3.1.2). The highest deficit volume is found in the humid continental climate (Dfb) and the lowest in the Mediterranean climate, irrespective of the identification method (Table **??** and **??**), although the deficit volumes differ per method.

The pan-European analysis of the river network (Table **??** and **??**, Fig. 3b). **??**, **??**, **??**, and **??**) evidently demonstrates that drought characteristics (occurrence, timing, average duration, average deficit volume) determined by commonly applied identification methods (variable threshold versus fixed threshold, daily versus monthly resolution, threshold versus standardized approach) are different. The differences are also dependent on the climate region.

Another clear distinction between VT drought timing and climate regions is also found in the Ebro River in Spain. The upstream part of the Ebro River is mainly located in the Cfb climate region where the water is coming from the Pyrenees mountains (Dfc and ET) , whereas the downstream part is located in the Bsk climate region. The timing of drought event in the upstream part is early (spring) , similar to the Rhine in the upstream part, which mixes the timings of Dfc, ET, and Cfb climates. The downstream part has similar drought timing than many other Cfb and Bsk climate regions, where drought starts at the end of summer to early winter. However, in contrary to VT drought, FT drought, SSI-6, and SSI-1 droughts in the Ebro River do not show different timingbetween upstream and downstream areas (Fig. 3b, c and A2) .

3.1.2 Drought occurrences in selected rivers and periods

For a more detailed analysis on of the differences of streamflow droughts derived from different indices, approaches, as illustrated above for the whole pan-European network, we investigated four rivers situated in main climates across Europe (Fig. 4 and 5) . Figure 4 and 5 **??**) for particular periods. The pan-European analysis focused on the spatial aspects of the differences between the drought identification methods, whereas the detailed analysis of the four selected rivers emphasizes the temporal aspects. Figure **??** and **??** show for some particular selected years a detailed analysis of drought in the rivers. The proxy observed flow (30DMA hydrograph) of the period 2000-2004 from the Rhine River in combination with the VT and FT clearly shows daily threshold methods (VTD and FTD) clearly show that streamflow drought mainly occurred from summer to autumn 2003 to January 2004 (Fig. 4a**??**a). The year 2003 is one of the most notable drought years in Europe (Fink et al., 2006; Ionita et al. , 2017; Laaha et al., 2017). During wet years, e.g. from 2000 to 2002, there were no streamflow drought events (both VT and FT)identified, although the lowest flows occurred in the end of summer season (referred to as the n-day annual minimum flow, which appears each year by definition, Hisdal et al. (2004)) . Drought in the Rhine River derived from SSI-6 shows that streamflow drought started in spring identified (both VTD and FTD). The difference in drought occurrence in the Rhine River in the selected 5-year period between the daily methods is small, for example, there are a few minor droughts detected (early 2003 and continued into 2005 summer, December 2004) with the VTD, whereas these were not found with the FTD. The deficit volume of the drought event in summer 2003 was clearly larger for the FTD than of the VTD. In the winter of 2003-2004, the opposite happened (Fig. 5a). This multi-year drought event (Tallaksen and Van Lanen , 2004) occurred because the 6-month accumulated Rhine streamflow was relatively low from 2003 to 2005 (1700-1800 m^3/s) compared with long mean annual average (>2000 m^3/s). One long drought event derived from SSI-6 is divided into four shorter SSI-1 drought events **??**a). The different identification approaches using monthly data (VTM, FTM, and SSI-1) also detected the 2003 drought as the major event in the 2000-2004 time series (Fig. 5a**??**a), which occurred in the beginning of terminated in October due to some precipitation. This precipitation had a more marked effect on the SSI-1 drought than on the VTM and FTM droughts. Some minor drought events were identified in autumn and winter 2003 to December 2003, January 2004 to July 2004, August 2004, and from September 2004 to 2005. A comparison between SSI-6 and with all three methods, although the timing was different. For instance, the SSI-1 droughts clearly shows that the frequency of SSI-1 drought is much higher than of SSI-6 (Vidal et al. , 2010) (see also Fig2c and A1was later than the FTM drought (Fig. **??**a).

In A difference between drought identification approaches using daily and monthly drought methods is clearly seen in the Danube River (Fig. 4b), FT and VT droughts in **??**b and **??**b). Many minor drought events were recognized using daily data, that is, in winters from 2000 to 2002, spring 2003 happened in August, whereas in the hydrological year and 2004 , only FT drought occurred in for FTD, and in spring 2003/, spring 2004winter (November 2003 to January , summer 2004). Similar to the Rhine River, in the Danube, a long SSI-6 drought started before summer of 2003 and covered the whole of 2004 (Fig. 5b). Figures 4b and 5b , and winter 2004/2005 for VTD. In contrast, minor drought events in winter 2001/2002 and in spring 2003 did not occur if we applied drought identification approaches using monthly data (FTM and VTM, respectively, Fig. **??**b). Figure **??**b and **??**b demonstrate that during rather wet years (the year 2000-2002), no VT and SSI-6 VTD, VTM, and SSI-1 droughts were observed. VT and SSI-6 droughts The VT and SSI-1 approaches take into account seasonality in their analyses. In contrast, many minor FT drought events were observed if the 30DMA approach would not have been applied to the streamflow data. In these years, several drought events were also seen in SSI-1 (Fig. 5bSimilar to the Rhine River, in the Danube, a major drought event in 2003 was identified using all approaches (Figure **??**b and **??**b).

Figure 4c shows that the Kemijoki River, In the Vuoksi River, which is located in the cold climate region (Fig. 1), is dominated by long baseflow periods. High streamflow was only observed at the end of the spring season and summer due to the snowmelt and high precipitation events . Unlike VT drought, which was only identified in the beginning of summer 2004 for short period, a FT drought with long duration and high deficit volume was observed from winter to end of spring 2004 due to delayed snowmelt. A multi-year Dfc, Fig. **??**), all drought identification approaches show more or less similar drought occurrences (Fig. **??**c and **??**c). The FT approaches, both at the daily and monthly scale, detect slightly more events than those that consider seasonality (VT methods and SSI-1drought and SSI-6 drought was observed from summer 2002 to the beginning of 2005 (Fig.5c). During these years, the spring peak streamflow was only half of the peak in the year 2000 and 2001.). Two multi-year drought events (Tallaksen and Van Lanen , 2004) were detected in 1999-2000 and 2002-2003 with all drought approaches. The main reason for this is that there is only a small difference between daily and monthly streamflow. The presence of water bodies, such as lakes, causes daily streamflow not to be highly variable in short term. This attenuates and damps the streamflow response to the driving force, i.e. precipitation, incl. snowmelt, and is thus driven by longer-term previous hydrological conditions (Pechlivanidis et al., 2020).

In the first decade of the 21st C, regions situated Century, climate variability in the Mediterranean experienced different climate variability regions caused different wet/dry periods compared to the rest of Europe. In contrast to the severe 2003 drought in central and west Europe, the most severe droughts in, e.g. Catalonia (Spain), were observed from 2005 to 2008 (Martin-Ortega et al., 2012; March et al., 2013), which is illustrated by the streamflow of the Ebro River that indicates drought events in these years (Fig. 4d and 5d). Nine FT drought events (30DMA)were observed from 2005 to **??**d and **??**d). Pronounced FTD droughts occurred every year in the period 2005-2009, whereas only minor VTD drought occurred in the last year (Fig, **??**d). Using monthly instead of daily streamflow data reveals a similar pattern (Fig. **??**d), i.e. no VTM droughts from summer 2008 , whereas only six VT droughts were observed. These to 2009, while these happened in all summers according to the FTM method. The droughts in 2005-2007 also illustrate differences in timing between VT and FT drought events from 2005 to methods, both at the daily and monthly scale, i.e. limited coinciding periods (orange-shaded in Fig. **??**d and **??**d). The SSI-1 droughts follow the pattern of VTM droughts. A multi-year drought event from summer 2007 to spring 2008 correspond with two and six SSI-6 and was identified with all approaches, although duration is different (e.g. FT droughts, FTD and FTM, lasted markedly longer than VT droughts, VTD and VTM, as well as SSI-1 droughtevents, respectively (Fig. 5d). In the hydrologic year2006). Another major drought event in the Ebro was observed in 2005. In contrast to the 2007-2008 drought in this year, the Ebro River experienced one VT drought and three FT droughts when applying the 30DMA and five VT droughtsand five FT droughts when the 30DMA was not used. This proves that application of the 30DMA results in less minor droughts and that the occurrence of FT and SSI-1 droughts in many rivers, not only in the Ebro River, is higher than the VT and SSI-6 droughts, as discussed above (Section 3.1.1considerably longer VTD, VTM, and SSI-1 droughts than FTD and FTM droughts.

Above we explained differences in drought characteristics derived from different identification methods for the four selected rivers for a 5-year period. A summary of the outcome from all five drought identification methods for the four selected rivers and all hydrological years (1991-2018) is presented in the Supplementary Material (Supplementary Table S1 and Table S2).

In general, our study on streamflow drought occurrences

3.1.3 Summary of differences between drought identification approaches

The more detailed drought analysis of the four selected rivers and the in the previous section and the broader analysis of the pan-European river network shows that the FT approach identifies more drought events and higher droughtdeficit volumes than the VT method, which contradicts with some previous studies (e.g., Sung and Chung , 2014; Heudorfer and Stahl , 2017) . These studies conclude that the VT approach yields a higher number of minor drought events and larger deficit volumes because those studies did not smooth streamflow and threshold data by applying e.g. 30DMA to reduce the occurrence of minor drought as we did (Section 2b). Another study by Sarailidis et al. (2019) for the Yermasoyia river basin (intermittent river)in Cyprus conclude that FT identifies lower number drought event but it yields higher deficit volume than VT, which is in between our study and studies conducted by Sung and Chung (2014) and Heudorfer and Stahl (2017) .

3.1.4 Summary of drought occurrences and timing in selected rivers

The number of streamflow droughts derived using different identification methods and (Section 3.1.1, Table **??** and **??**) show that the FTD approach identifies a lower number of drought events than the VTD. On the other hand, when monthly approaches are used to detect drought, the FTM approach results in slightly more droughts than the VTM. Clearly, relative differences are smaller than for the daily resolution. Sarailidis et al. (2019) found for the Yermasoyia catchment (Cyprus) a smaller number of droughts both at the monthly and daily resolution when applying the timing for the fixed threshold instead of the variable threshold, which is in line with our daily results (FTD versus VTD). Overall, early droughts were identified using the fixed threshold methods, irrespective of the temporal resolution (FTD and FTM). Rivers located in the Dfb climate, however, have later FT droughts than the VT droughts. The FTD identifies longer droughts than the VTD, whereas the differences in average duration when using the monthly resolution (FTM and VTM) are small. Our findings on drought duration at the daily time scale are also found by Heudorfer and Stahl (2017) in a study dealing with four case catchments in Germany. In the pan-European analysis (Table **??** and **??**), we found that the drought deficit volume obtained with the VT methods (VTD and VTM) is slightly higher than with the FT methods (FTD and FTM). This is confirmed by a study done by Sung and Chung (2014) for the Seomjin River basin in Korea. Not all four selected rivers are summarized in Table 1 for follow this pattern, for instance, in the Rhine and Danube, application of the hydrological years 1991 to 2018. We ranked the timing of drought for the two or three months, in which drought most frequently occurred starting by FT methods results in higher deficit volumes than the VT methods (Supplementary Table S1 and S2), which is also found by Sarailidis et al. (2019) in the Yermasoyia catchment. Obviously, individual rivers may deviate from the general pattern. Our generic finding that the streamflow drought characteristics (frequency, duration, timing) depend on the identification method is in line with the observations made by Vidal et al. (2010), who for streamflow drought in France also concluded that the identification method, although different (only standardized-based indices at multiple time scales) from our study, is crucial.

3.2 Implication of different drought identification approaches to forecast streamflow drought

So far, this paper has focused on a historical drought analysis using different identification approaches, which creates a base for the implications of these findings for the forecasting of streamflow drought. First, we illustrate the implications at the pan-European scale with focus at the spatial aspects followed by a more detailed temporal analysis for the month with the highest occurrence, followed by the month with the second highest occurrence, etc (descending order) . The highest number of VT droughtevents was found in the Ebro River followed by the Rhine River, as one of the four selected rivers above. The 2003 drought is used as an example.

3.2.1 Forecasting streamflow drought characteristics across Europe

Consequences of using different drought identification approaches to forecast streamflow drought characteristics across Europe are described in this section. The forecast initiated in the first of July 2003 (median of 25 ensemble members) for 7 months ahead (up to January 2004, see Section 2.3 for the calculation of drought characteristics using forecast data) is used for illustration. We show the forecasted drought duration and timing here (Fig. **??** and **??**, respectively), while the forecasted frequency of drought occurrences and drought deficit volumes are provided in appendix B.

Figure **??** shows the forecasted average drought duration in Europe using the forecast initiated in July 2003 for a 7-month lead time (July 2003-Jan 2004). Longer drought duration is forecasted in many European rivers using the FT approaches (FTD and FTM, Fig. **??**b and **??**d) than the VTs (VTD and VTM, Fig. The Kemijoki and Danube Rivers have the same number of VT droughts (17 events). The frequency of FT droughts is higher than VT droughts (except for **??**a and **??**b), up to 60 days/2 months, which for the daily resolution was expected based on the historic analysis (up to ∼20%, Table 1). The SSI-1 approach forecasts similar drought duration to VTM (Fig. **??**e and **??**c). Using the VT and SSI-1 approaches, drought was forecasted to last on average 40 days or ∼1 month in the Rhine River) . The Ebro River has the highest occurrence of FT droughts (35 events) followed by the Danube River (32 events). The Kemijoki and Rhine Rivers have a lower number of FT drought events than the two other rivers. The occurrence of SSI-6 drought is, in general, close to VT drought around 18 events, except in Ebro (only 14 SSI-6 drought events). period July 2003-Jan 2004 in many European rivers. The FT methods predict an average duration of 120 days or ∼4 months. Rivers located in Eastern European countries, such as in Belarus, Ukraine, and Romania were predicted to have a long drought duration in the above-mentioned period according to all approaches (up to 200 days, 7 months, Fig. **??**). This region (the eastern part of Europe) is identified as an area suffering from severe hydrological drought hazards, where the frequency of drought is small compared to other European regions, but with the drawback that droughts last long (Sutanto and Van Lanen , 2020). The forecasted average drought durations in the Cfb, Dfc, and Mediterranean climates using the FT approaches are around 100 days for FTD and 3-4 months for FTM (Fig. ??b and ??d), which is almost threefold longer than obtained with the VT approaches.

Another distinction among drought indices is to be seen in the timing of these events, except for Rhine. In the Rhine River (downstream, see Fig. 2)streamflow drought mostly occurred in spring for all indices (April), followed by in the beginning of winter and in autumn. VT Figure ?? presents the forecasted number of drought events from July 2003 to January 2004 (LT=7) derived from different drought approaches. In general, the VT (VTD and VTM) and SSI-6 droughts happening in December are caused by sustained low flows in the end of summer and autumn. Minor drought events in spring can be related to the warm snow season drought SSI-1 approaches forecast that at least one drought event would occur in lots of river grid cells in Europe ($\sim$80%, Fig. ??a, ??c, and ??e), which is lower than the number of droughts forecasted with the FT approaches ($\sim$90%, Fig. ??b and ??d). These differences in drought frequency between identification approaches are not uniformly distributed over Europe. For instance, in the upstream area, as explained above (Section 3.1.1). In the Danube, VT drought occurred in a wide range of months (spring, end of winter season, and summer), while the FT drought commonly occurred at the end of autumn and winter. SSI-6 differs from VT and FT in the Danube. SSI-6 drought mainly occurred in winter and beginning of spring. In the Kemijoki River (Dfc) , VT drought has timing in late winter and early spring, just before the high streamflow starts (?) (see also Fig. 4c). This is typical for rivers in a subarctic climate, where the snowmelt process generates peak streamflow in early summer, the Cfb and Dfb climates, the opposite is found, that is, May or June (??). FT drought , on the other hand, mostly occurred in winter and early spring. SSI-6 drought in Kemijoki has a different timing compared to others. Start of drought was mostly observed in late spring and in autumn. The Ebro River has VT drought that starts in early spring and autumn. This likely iscaused by the lack of heavy precipitation associated with convective weather events that normally occur in spring and autumn (?van Hateren et al., 2019). Moreover, the VT drought that occurred in autumn (November) can also be triggered by sustained low flows that started in summer and continued in autumn (from August to October). Drought identification using the FT approach in the Ebro River shows that events mostly occurred in the summer (July VT methods forecast higher drought frequency than FT methods. The differences in the number of drought occurrences between the identification approaches highlight the importance of considering whether seasonality should be taken into account (VT and SSI-1 droughts) in the forecasting, or not (FT droughts).

The forecasted drought start in the period July 2003-Jan 2004 (month that the first drought appears, see Section 2.3 for the determination of the start month/timing) using the VT approaches and SSI-1 is, in general, later than of the FT approaches, except in the cold regions, such as Dfc and ET (Fig. ??). In the Cfb, Dfb, and Mediterranean climates, the VT and August)prior to the SSI-6 drought. SSI-1 approaches predict the drought timing in September to December (Fig. ??a, ??c, and ??e), while the start of the forecasted FT droughts is earlier, i.e. July to September (Fig. ??b and ??d). It is vice versa for the Dfc region (Sweden and Finland), where forecasted VT and SSI-1 droughts are earlier (July) than FT droughts (December and January). Higher drought deficit volume than 2000 m^3 is predicted for the period July 2003-Jan 2004 in many European rivers using the FT approaches than those predicted with the VTM ones (Fig. ??). An exception is seen for some big rivers flowing through

Hungary, Ukraine, Romania, and Bulgaria. Both VT and FT drought have a high deficit volume predicted there, because of the long drought durations (Fig. **??**).

3.3 Implication of the identification approaches to forecast streamflow drought

So far this paper has focused on the historical drought analysis using different identification approaches , which creates a base for the implications of the findings for streamflow drought forecasting. This section describes in detail an exampleof the consequences of using different drought identification approaches to forecast streamflow drought. Figure 6 illustrates the forecasted streamflow

3.2.1 Forecasted drought characteristics for the Rhine River

In the previous section we have dealt with streamflow forecasting for the pan-European river network that mainly focusses on spatial aspects. Here, we concentrate more on the temporal aspects, and use the Rhine River as an example. Figure **??** illustrates the proxy observed and forecasted 25 ensemble streamflows (grey shaded area) in the Rhine River (location 1, Fig. **??**) initiated in August April and July 2003 for 5 months ahead (purple line), incl. 25 ensemble members (grey shaded area) and the 7 months ahead and the forecasted median ensemble streamflow (purple line) using all drought identification methods. In addition, the forecasted droughts in streamflow using different identification approaches are given (shaded areas below VT and FT). August thresholds). We choose the 7-month forecast initiated in April 2003 (Fig. **??**a, **??**c, and **??**e) covering spring, summer, and autumn to explore if the forecasts obtained with different identification methods are able to predict drought that occurred in summer 2003. July 2003 was chosen because streamflow drought based on observations (SFO) was starting from in this month (see Fig. 4a). Clearly, meteorological drought started earlier. FT drought forecast done in August **??**a). VTD and FTD drought forecasts done in April using the median ensemble identifies a drought event that occurred from end of August to mid September (Fig. 6aidentify a minor drought that occurred in April (orange area) and from August to October only for FTD (red areas), i.e. the purple line is below the red line. The FT approach forecasts adrought deficit volume of 1, 217 m^3 for blue (VT) and the red line (FT) (Fig. **??**a). The forecast done in April (Fig. **??**a) also shows that some dry ensemble members predict two long-lasting droughts, both for FTD and VTD, that is, from mid April to early June, and from August to the end of the forecast record (October). On the other hand, some other ensemble members do not predict any drought at all in the duration of 29 days (red area, Fig. 6a). The VT method, however, could not detect drought and could have performed better in this case. The median streamflow is forecasted slightly higher than the VT threshold and consequently no drought is predicted. April-October forecast record. VTD and FTD drought forecasts done in July using the median ensemble identify minor drought events that would occur in July and November (orange areas), whereas a major FTD drought would happen from the end of July to the end of October (Fig. **??**b). In general, the FTD method forecasts more drought events in 2003 than the VTD (Fig. **??**a and **??**b).

In contrast to the daily threshold approaches, the 25 ensemble drought forecasts done in August April 2003 using the standardized approach (SSI-6) show a long drought event , with SSI-6 that varies between -0.3 and -2.7 (mild to extreme drought)monthly drought identification approaches, VTM, FTM, and SSI-1, do not forecast a drought event that would occur in summer (Fig. ??c and ??e, see Fig. ??a for observed drought). A minor drought event is predicted with the FTM method by the end of December (Fig. 6b). Based on median ensemble, a mild SSI-6 drought was forecasted for the Rhine at the beginning of August that increased to severe drought in the end of December.

Figure 6c shows drought forecasts the forecasts, which is September (red shaded area). Monthly drought forecasts done in July 2003 predict a FT drought from August to the end of September (Fig. ??d). This indicates that all the forecast approaches miss the ongoing drought event in July, as it was observed (Fig. ??a). The VTM approach, on the other hand, does not predict any drought event, whereas the SSI-1 forecasts a minor drought event in the beginning of July, but no other droughts later in 2003 are forecasted (Fig. ??f).

In general, drought events (i.e. occurrence) can relatively be well forecasted using the median of ensemble members, but this holds to a lesser extent to other drought characteristics, such as severity, duration, and deficit volume. Additional metrics than the median, such as 25th and 10th percentiles taken from the ensembles, must also be considered for drought forecasting, as done by Sutanto et al. (2020a). Figure ?? clearly demonstrates that the observed streamflow is placed in between the lowest ensemble member and the ensemble median during a severe drought event, as the 2003 drought. Irrespective of the skill, the forecasts of the drought for the Rhine River using VT and FT without applying the smoothing procedure (30DMA). Three drought events were forecasted : one in August (both VT and FT indicated by blue and red areas, respectively) , one in the end of September (FT, red area), show that predicted drought characteristics very much depend on the identification method, incl. the temporal resolution (daily versus monthly).

For a better overview of forecasted drought characteristics in the Rhine River than in Figure ??, we summarize all 7-month forecast results done from January 2003 to December 2003 in Table ?? for daily drought approaches (VTD and FTD) and in Table ?? for monthly drought approaches (VTM, FTM, and SSI-1) using the median of the ensemble members. This implies that not only the April and July forecasts are considered, as done in Figure ??, but also forecasts done in all the other months of 2003, meaning that the December forecast covers the first six months of 2004. The forecasts initiated in January, February, and March using daily data (Table ??) did not predict any drought event in 2003 (except for some ensemble members, Ne>0). Droughts were predicted not earlier than forecasts issued in April. In April, three minor VTD droughts and nine minor FTD droughts were predicted to occur with average drought duration of 2.7 and one in the end of October (minor FT drought , red area). FT drought analysis without 30DMA procedure will produce more 6.1 days, respectively. The timing shows that droughts will start in April (VTD) and September (FTD). For drought events forecasted in April using the VTD method, the maximum number of ensemble members (Ne) foreseeing these three minor drought events with shorter duration (24 days in August, 18 days in September, and four days in October) . The 30DMA FT drought in August events in the period April-October is 88% (22 members out of 25 fall below the threshold). The FTD method shows the same number of members (22 members, 88%). The number of ensemble members in drought (Ne in %) can be used as a measure for drought forecast uncertainty or the forecast confidence level. The higher the percentage, the more likely the drought will occur (higher confidence level). In our case, VTD and FTD droughts were predicted to occur in the Rhine River with a high confidence level (Ne=100%) starting from July until at least the end of the year 2003. The forecast issued in July 2003 has drought duration of 29 days(see Fig. 6a) , which is five dayslonger than without 30DMA application. In total, the FT approach without 30DMA procedure forecasts a predicts the highest number of VTD drought events up to 14 events with an average duration of 2.8 days. The FTD method shows a lower drought frequency (9 events) but with a longer average duration (12.7 days). The longest average drought duration was predicted by the VTD forecast initiated in October (24 days) and in June for FTD (28.7 days). For the drought deficit volumeof 5, 047 , the highest water deficit was predicted using forecast initiated in October and December for VTD (4,502 m^3 in 46 days for the period from August to December 2003. VT drought was only predicted to occur in Augustwith a drought deficit volume of 2,101 and 10,654 m^3over 18 days. , respectively) and in August and December for FTD (5,877 m^3 and 14,720 m^3, respectively).

Although VT drought in the example of August 2003 could not be predicted using the 30DMA, a moving average method (e.g. the 30DMA)is commonly applied to reduce minor drought events as shown in some studies (e.g., Fleig et al., 2006; van Loon and van Lar . For drought forecasting, it is also encouraged to use monthly averaged streamflow data, by for instance, aggregating the data into monthlyThe monthly drought approaches, on the other hand, show different results from the daily approaches for most of the characteristics (compare Table **??** and **??**). The FTM method predicts one drought event in each of the forecasts initiated from April to December with medium to high confidence (Ne>50%). The VTM method foresees one or two events from the May forecast onwards with a medium to high confidence level (Ne>50%). The SSI-1 method starts predicting droughts two or three months later than the threshold approaches. The longest predicted VTM drought (two months) and most severe (total deficit volume: 10,210 m^3) was done by the forecast initiated in September. The longest FTM drought was predicted (up to 4 months) with the forecast initiated in August. This FTM drought also has the highest drought deficit volume (32,883 m^3). The analysis of the forecasts from January to December for the Rhine River (Table **??** and **??**) clearly shows that forecasted drought characteristics depend on the identification method.

In this study, we highlight the occurrence of minor droughts derived with the daily threshold methods (VTD and FTD) as a reason for the high drought frequency (Fig. **??**a, Fig. **??**b, Fig. **??**, Fig. **??**, Fig. **??**, Fig. **??**, Table **??**, and Table **??**). A high number of VTD minor droughts with short duration and small deficit volume may disturb drought analysis. Tallaksen et al. (1997) and Fleig et al. (2006) suggest several pooling procedures to reduce the number of minor droughts, such as the use of the Standardized Indices or applying 30DMA (e.g., **??**Dutra et al., 2014; Trambauer et al., 2015; Sutanto et al., 2020a; van Ha . The use of monthly averaged data or 30DMA will alleviate the drought forecast skill as shown in those studiesapplying the inter-event time method (IT-method), the moving average procedure (used in this study), and the sequent peak algorithm (SPA). They state that minor droughts are automatically filtered out when the moving average procedure is applied. In our case where study, however, this only happens to a certain extent. As expected, when we would not have applied the 30DMAVT drought could not be detected , the number of drought occurrences would have been higher, i.e. in this case by a factor of three (Fig. 6a), this might be due to the Q90 threshold applied in our analysis that only identifies rare extreme drought events compared to lower thresholds, such as Q70 and Q80 (Tallaksen et al. , 1997; van Loon and van Lanen , 2012). The SSI-6 also predicts moderate drought in August 2003 (-1>SSI≥-1.5)and severe drought in October 2003 (-1.5>SSI≥-2) while no extreme drought was forecasted (SSI**??**a and **??**).

In addition to these pooling techniques, the exclusion of drought events with duration shorter than a given number of days is recommended (Jakubowski and Radczuk , 2004; van Loon et al. , 2012). For example, van Loon et al. (2012) excluded droughts that have duration less than three days, van Loon and van Lanen (2012) excluded droughts that have duration fewer than 15 days, and some studies excluded droughts that have duration less than five days (Hisdal et al. , 2004; Birkel , 2005; Fleig et al., 2006 . In the end, the choice to exclude drought events shorter than a particular number of days to avoid minor droughts in the drought analysis, is a matter of subjectivity. We showed in our analysis that if we would have excluded drought < ~~-2, Fig~~30 days (Fig. **??**), the number of drought occurrences in most of the European rivers would decrease by 60% (Section 3.1.1) In this study, although we excluded many minor drought events by applying moving average procedures, which is the 30DMA for drought analyses (Section 2.2.1), minor drought events are still there (Fig. **??**). In this study, we did not apply pooling procedures, as mentioned above, besides the 30DMA. ~~6b).~~

4 Conclusions

Streamflow drought forecasting ~~involves~~ may use different identification approaches to ~~identify drought .~~ detect drought events, i.e. threshold and standardized approaches. This study presents a ~~historical drought analysis for~~ drought analysis using simulated historical streamflow data from the pan-European rivers ~~, incl. a more detailed investigation of four selected rivers~~ network. It consists of almost 30,000 river grid cells and is located in different climates across Europe~~using commonly applied~~ . We applied commonly identification approaches, which are the daily Variable Threshold (~~VT~~VTD), the daily Fixed Threshold (~~FT~~FTD), and the Standardized Streamflow Index (~~SSI-6) .~~ SSI-1) that uses aggregated streamflow over a month. In addition, we also provide results derived from monthly threshold approaches (VTM and FTM) for a fair comparison with the SSI-1 drought. These approaches generate ~~different drought outcome. The main difference between VT, FT, and SSI-6 droughts was found in the number of~~ several drought characteristics, namely frequency, duration, timing, and deficit volume (latter not for SSI-1). The largest difference amongst the drought identification approaches comes from the temporal resolution. When using the same drought identification approach (variable or fixed threshold methods), but using different data aggregation levels (daily versus monthly), the daily methods evidently generate more drought occurrences. The ~~occurrence of drought derived using the FT method is higher than the~~ daily variable threshold method (VTD) detects almost twice as many drought events as the monthly method (VTM). The FTD also identifies more drought events than the FTM, but deviation is smaller (about 25%). Minor droughts shorter than 1 month are the main reason for the higher number of drought ~~events derived using the VT or SSI-6 approach (except SSI-1), which highlights the importance whether end-users of drought forecasts would take seasonality into account or not for their purpose. In addition, the FT method produces higher drought deficit volumes and duration than VT.~~ occurrences identified by the daily threshold methods (VTD and FTD). The frequency of drought occurrences derived from the VTD approach is higher than obtained with the FTD, whereas the differences amongst methods using monthly data (VTM, FTM and SSI-1) is rather small (<15%).

Identification of streamflow droughts using different methods also affects timing, i.e. the month in which the ~~event~~ drought starts. Differences are ~~strongly~~ also controlled by climate regions. ~~For instance, in the temperate oceanic climate and Mediterranean climate , FT droughts mostly occurred in~~ In general, the ~~summer (July and August) . The start of VT and SSI-6 droughts is~~

~~later. We also found that, in general, the occurrence and timing of FT droughts are close to what being identified by the SSI-1 index and VT droughtsare more similar to SSI-6.~~

~~Drought forecasting requires multi-monthly or seasonal time horizons, as drought is a slowly-develop natural disaster that can~~ fixed threshold methods (FTD and FTM) detect earlier drought than the fixed threshold methods (VTD and VTM), except many rivers the humid continental climate (Dfb). Rivers located in cold climate regions (ET, Dfb and Dfc) experience streamflow drought events in late winter and early spring (March-April) when the daily variable threshold method (VTD) is applied, and later when monthly data (VTM) are used (May-July). When using the fixed threshold methods not such clear pattern in the start of the drought in the cold climates was found (FTD: February-June, and FTM: February-July). Drought in the Mediterranean climate mostly starts late, in late summer or autumn (August-October), irrespective of the identification method. The start of SSI-1 droughts is closest to VTM droughts. Average drought duration for the threshold methods is more controlled by the number of occurrences (i.e. negatively correlated). This implies that the drought duration obtained with the daily threshold methods (VTD and FTD) is shorter than derived from the monthly methods (VTD and VTM), and that the FTD droughts last longer than ~~a month up to seasons or years. For streamflow drought ,~~ VTD droughts. In addition, the methods using daily data produce drought events with lower drought deficit volumes (25-30%) than the methods fed with monthly data. It is important to note that the findings for the whole pan-Europe river network are generic. Individual rivers, as illustrated with some selected rivers, may deviate from the general pattern.

The different drought identification approaches were also applied to streamflow forecasting with the ~~threshold approaches have to be applied with caution, in particular the temporal aggregation has to be considered. The use of aggregated daily streamflow data into monthly time windows, such as the application of 30-day Moving Average (30DMA), is recommended as applied in this study for the identification of VT and FT droughts. This approach will eliminate the undesired minor drought events, which are identified when using non-aggregated daily flow data , and also increase the drought forecast skill. The use of monthly-aggregated forecasted flow data (e. g. SSI) is the best practice for seasonal drought forecasts . This method, however, cannot be used to calculate~~ 2003 drought as an example, which yielded similar conclusions to the historical analysis. The forecasted average drought duration across Europe done in July 2003 clearly differs between the daily and monthly approaches, in particular the VTM and SSI-1 predict lower average duration for the upcoming 7 months. The seasonal forecasts issued each month in 2003 for the Rhine River supports the substantial differences in forecasted drought characteristics amongst methods using daily or monthly data and between variable and fixed threshold methods. The differences in drought frequency, average duration, timing, and deficit volumes between VT droughts (incl. SSI-1) and FT droughts highlight the importance of whether end-users of drought forecasts should take seasonality into account or not. Moreover, the temporal resolution of drought identification, that is, the use of daily or monthly data, is critical to consider. When the drought deficit volume ~~, which is a key component for water managers coping with hydrological drought. If deficit volumes are requiredfor decision making, then threshold approaches (VT or FT) should be applied on 30-day averaged flow data~~is required, then the standardized approach (SSI) cannot be selected. The choice of the drought identification method when forecasting streamflow drought, in the end, lies ~~to~~ in the end-users specific requirements and decisions, and there is no one drought identification approach that fits all needs. For this particular reason, the European DEWSs, such as the European

Drought Observatory (EDO, Sepulcre-Canto et al., 2012) and the Anywhere DEWS (ADEWS, Sutanto et al., 2020a) forecast both standardized-based and threshold-based drought indices.

Our study, both the historical analysis and the forecasting, clearly shows that streamflow droughts obtained from different drought identification approaches (variable threshold (daily versus monthly), fixed threshold (daily versus monthly), and standardized ~~approaches) differ both in the occurrence and timing, including the forecasts of these events~~index) differ in terms of their drought characteristics. Often scientists have analyzed and provided streamflow drought forecasts without clearly defining the identification method. This created misconceptions, miss-citations, and confusion among the academic community (authors, reviewers, editors), operational weather and water services, as well as end-users, which consider drought forecast products and associated terminology as interchangeably. Our study recommends scientists, developers of Drought Early Warning Systems, and end-users to clearly agree among themselves, preferable in a co-design phase, upon a sharp definition of which type of streamflow drought is required to be forecasted to mitigate the impacts of drought. Obviously, Drought Early Warning Systems also can include more than one drought identification method, as illustrated by Sutanto et al. (2020a). Then the end-user can decide in the end, which forecast product is most adequate based upon the provided description of the identification method and product.

Data availability. The streamflow EFAS data are accessible under a COPERNICUS open data license (https://doi.org/10.24381/cds.e3458969). In this study, we used EFAS system version 3. The SSI-1 analyzed using the SFO data and re-forecasts are available online in the 4TU Centre for Research Data with doi:10.4121/13056071.v1.

Appendix A: Drought ~~occurrence and timing deriverd~~ characteristics obtained from ~~SSI-1~~historical data

~~In Figure A1~~Appendix A includes drought characteristics obtained using proxy observed (SFO) data from 1990 to 2018. In Figure **??**, we present the number of ~~streamflow drought occurrences identified using the Standardized Streamflow Index with an accumulation time of one month (SSI-1)~~minor drought occurrences that have duration less than 30 days. Streamflow drought was ~~calculated using the SFO data from 1990 to 2018. Occurrence~~ identified using the VTD approach. Figure **??** and **??** show the average duration of streamflow drought ~~derived from SSI-1 is higher than SSI-6 (Fig. 2c), which is more than 70 events in some regions, such as in the UK and Norway. Figure S2 shows the timing of streamflow drought~~ and average drought deficit volume in the European rivers identified with different drought identification approaches, namely the VTD, FTD, VTM, FTM, and SSI-1. Figure **??** illustrates the number of drought occurrences in European rivers from October 1990 to September 2018 (28 years) identified using the ~~SSI-1.Major difference between~~ VTD approach without smoothing, i.e. applying the 30DMA method.

Appendix B: Forecasting drought occurrence and deficit volume

Appendix B describes forecasted drought characteristics in major European rivers obtained from the forecast initiated in July 2003 for 7 months ahead (up to January 2004). Drought characteristics were derived using different drought identification approaches, namely the VTD, FTD, VTM, FTM, and SSI-1and SSI-6 (Fig. 3c) in term of drought timing is located in the Dfb (central and east Europe)and Dfc climate regions (north Europe). In these regions the timing of SSI-1 is in winter and spring, which deviates with the timing of SSI-6 in autumn. Figure **??** and **??** show forecasted drought occurrences and forecasted average drought deficit volume, respectively.

Author contributions. S.J.S and H.A.J.V.L conceived and implemented the research. Data analyses, model output analyses, and all figures have been performed by S.J.S. S.J.S and H.A.J.V.L wrote the initial version of the paper and equally contributed to interpreting the results, discussion, and improving the paper.

Competing interests. The authors declare no competing financial and/or non-financial interests in relation to the work described.

Acknowledgements. The research is supported by the ANYWHERE project (Grant Agreement No.: 700099), which is funded within EU's Horizon 2020 research and innovation program (www. anywhere-h2020.eu). www.anywhere-h2020.eu. The streamflow data came from the EFAS computational center, which is part of the Copernicus Emergency Management Service (EMS) and Early Warning Systems (EWS) funded by framework contract number 198702 of the European Commission. We thank Fredrik Wetterhall (ECMWF) for providing the EFAS data and two anonymous reviewers that helped to substantially improve the paper. This research is part of the Wageningen Institute for Environment and Climate Research (WIMEK-SENSE) and it supports the work of UNESCO EURO FRIEND-Water and the IAHS Panta Rhei program of Drought in the Anthropocene.

References

Arnal, L., Asp, S.-S., Baugh, C., De Roo, A., Disperati, J., Dottori, F., Garcia, R., Garcia-Padilla, M., Gelati, E., Gomes, G., Kalas, M., Krzeminski, B., Latini, M., Lorini, V., Mazzetti, C., Mikulickova, M., Muraro, D., Prudhomme, C., Rauthe-Scho¨ch, A., Rehfeldt, K., Salamon, P., Schweim, C., Skoien, J.O., Smith, P., Sprokkereef, E., Thiemig, V., Wetterhall, F., and Ziese, M.: EFAS upgrade for the extended model domain-technical documentation. Publications Office of the European Union, Luxembourg, EUR 29323 EN (ISBN 978-92- 79-92881-9), https://doi.org/10.2760/ 806324, 2019.

Arnal, L., Cloke, H. L., Stephens, E., Wetterhall, F., Prudhomme, C., Neumann, J., Krzeminski, B., and Pappenberger, F.: Skilful seasonal forecasts of streamflow over europe?, Hydrol. Earth Syst. Sci., 22, 2057–2072, https://doi.org/10.5194/hess-22-2057-2018, 2018.

Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised indicators, Hydrol. Earth Syst. Sci., 20, 2483–2505, doi:10.5194/hess-20-2483-2016, 2016.

~~Barrera-Escoda, A., and Llasat, M. C.: Evolving flood patterns in a Mediterranean region (1301-2012) and climatic factors-the case of Catalonia, Hydrol. Earth Syst. Sci., 19, 465–483, doi:10.5194/hess-19-465-2015, 2015.~~

Bell, V. A., Davies, H. N., Kay, A. L., Brookshaw, A., and Scaife, A. A.: A national-scale seasonal hydrological forecast system: development and evaluation over Britain, Hydrol. Earth Syst. Sci., 21, 4681-4691, 2017.

Belayneh, A., Adamowski, J., Khalil, B., and Ozga-Zielinski, B.: Long-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet neural network and wavelet support vector regression models, Journal of Hydrology, 508: 418-429, https://doi.org/10.1016/j.jhydrol.2013.10.052, 2014.

Beyene, B. S., Van Loon, A. F., Van Lanen, H. A. J., and Torfs, P. J. J. F.: Investigation of variable threshold level approaches for hydrological drought identification, Hydrol. Earth Syst. Sci. Discuss., 11, 12765–12797, https://doi.org/10.5194/hessd-11-12765-2014, 2014.

Birkel, C.: Temporal and Spatial Variability of Drought Indices in Costa Rica, Master's thesis, Albert-Ludwigs-Universität, Freiburg, Germany, 2005.

Burek, P., van der Knijff, J., and Roo, A. D.: LISFLOOD distributed water balance and flood simulation model, JRC Tech. Report, https://doi.org/102788/24719, 2013a.

Burek, P., van der Knijff, J., and Ntegeka, V.: LISVAP Evaporation Pre-processor for the LISFLOOD water balance and flood simulation model, JRC Tech. Rep., EUR26167EN, doi:10.2788/26000, 2013b.

Changnon, S. A.: Detecting drought conditions in illinois, Champaign Circular 169, Illinois State Water Survey, 36 pp., [ISWS/CIR-169/87], 1987.

Clark, M. P., and Hay, L. E.: use of medium-range numerical weather prediction model output to produce forecasts of streamflow, Journal of Hydrometeorology, 5, 15-32, 2004.

Cloke, H., Pappenberger, F., thielen, J., and thiemig, V.: Operational European flood forecasting, in: Environmental Modelling: Finding Simplicity in Complexity, 2nd edn., Wainwright, J. and Mulligan, M. (Eds.). John Wiley and Sons, Ltd, Chichester, UK, https://doi.org/10.1002/9781118351475.ch25, 2013.

Day, G. N.: Extended Streamflow Forecasting Using NWSRFS, Journal of Water Resources Planning and Management, 111(2), 157-170, 1985.

Ding, Y., Hayes, M., and Widhalm, M.: Measuring economic impacts of drought: a review and discussion, Disaster Prevention and Management, Vol. 20 No. 4, pp. 434-446, https://doi.org/10.1108/09653561111161752, 2011.

Duan, Q., Pappenberger, F., Wood, A., Cloke, H. L., and Schaake, J. C.: Handbook of Hydrometeorological Ensemble Forecasting, Springer, https://doi.org/10.1007%2F978-3-642-39925-1, 2019.

Dutra, E., Pozzi, W., Wetterhall, F., Di Giuseppe, F., Magnusson, L., Naumann, G., Barbosa, P., Vogt, J., and Pappenberger, F.: Global meteorological drought – Part 2: Seasonal forecasts, Hydrol. Earth Syst. Sci., 18, 2669–2678, doi:10.5194/hess-18-2669-2014, 2014.

Feyen, L., and Dankers, R.: Impact of global warming on streamflow drought in Europe, J. Geophys. Res., 114, D17116, doi:10.1029/2008JD011438, 2009.

Fink, A. H., Brücher, T., Krüger, A., Leckebusch, G. C., Pinto, J. G., and Ulbrich, U.: The 2003 european summer heatwaves and drought-synoptic diagnosis and impacts, Weather, Royal Meteo. Soc., 59, 209–216, doi:10.1256/wea.73.04, 2006.

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

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., and Bianchi, A.: Ensemble projections of future streamflow droughts in Europe, Hydrol. Earth Syst. Sci., 18, 85–108, doi: 10.5194/hess-18-85-2014, 2014.

Fundel, F., Jörg-Hess, S., and Zappa, M.: Monthly hydrometeorological ensemble prediction of streamflow droughts and corresponding drought indices, Hydrol. Earth Syst. Sci., 17, 395-407, doi:10.5194/hess-17-395-2013, 2013.

Gu, L., Chen, J., Yin, J., Sullivan, S. C., Wang, H-M., Guo, S., Zhang, L., and Kim, J-S.: Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 and 2°C warmer climates, Hydrol. Earth Syst. Sci., 24, 451–472, https://doi.org/10.5194/hess-24-451-2020, 2020.

Haile, G. G., Tang, Q., Sun, S., Huang, Z., Zhang, X., and Liu, X.: Droughts in East Africa: Causes, impacts and resilience, Earth-Science Reviews, 193, 146–161, https://doi.org/10.1016/j.earscirev.2019.04.015, 2019.

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., and Prudhomme, C.: Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit, Hydrol. Process., 25, 1146-1162, doi:10.1002/hyp.7725, 2011.

Heudorfer, B., and Stahl, K.: Comparison of different threshold level methods for drought propagation analysis in Germany, Hydrology Research, 48.5, 1311-1326, doi:10.2166/nh.2016.258, 2017.

Hisdal, H., Tallaksen, L. M., Clausen, B., Peters, E., and Gustard, A.: Hydrological Drought Characteristics. In: Tallaksen, L. M. & Van Lanen, H. A. J. (Eds.) Hydrological Drought, Processes and Estimation Methods for Streamflow and Groundwater. Development in Water Science 48, Elsevier Science B.V., pg. 139-198, 2004.

Ionita, M., Tallaksen, L. M., Kingston, D> G., Stagge, J. H., Laaha, G., Van Lanen, H. A. J., Scholz, P., Chelcea, S. M., and Haslinger, K.: The european 2015 drought from a climatological perspective, Hydrol. Earth Syst. Sci., 21, 1397–1419, doi:10.5194/hess-21-1397-2017, 2017.

IPCC.: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp, 2014.

Jakubowski, W., and Radczuk, L.: Estimation of Hydrological Drought Characteristics, NIZOWKA2003 – Software Manual, on accompanying CD to: Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater, edited by: Tallaksen, L. M. and van Lanen, H. A. J., Developments in Water Science, 48, Elsevier Science B.V., Amsterdam, 2004.

~~Korhonen, J., and Kuusisto, E.: long-term changes in the discharge regime in Finland, Hydrology Research, 41.3-4, 253-268, doi:10.2166/nh.2010.112, 2010.~~

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J-P., Stahl, K., Prudhomme, C., Heudorfer, B., Vlnas, R., Ionita, M., Van Lanen, H. A. J., Adler, M-J., Cailouet, L., Delus, C., Fendekova, M., Gailliez, S., Hannaford, J., Kingston, D., Van Loon, A. F., Mediero, L., Ozuch, M., Romanowicz, R., Sauquet, E., Stagge, J. H., and Wong, W. K.: The european 2015 drought from a hydrological perspective, Hydrol. Earth Syst. Sci., 21, 3001–3024, doi:10.5194/hess-21-3001-2017, 2017.

March, H., Domènech, L., and Saurí, D.: Water conservation campaigns and citizen perceptions: the drought of 2007-2008 in the Metropolitan area of Barcelona, Nat. Hazards, 65, 1951-1966, doi:10.1007/s11069-012-0456-2, 2013.

Martin-Ortega, J., González-Eguino, M., and Markandya, A.: The costs of drought: the 2007/2008 case of Barcelona, Water Policy, 14, 539-560, doi:10.2166/wp.2011.121, 2012.

Marx, A., Kumar, R., Thober, S., Rakovec, O., Wanders, N., Zink, M., Wood, E. F., Pan, M., Sheffield, J., and Samaniego, L.: Climate change alters low flows in Europe under global warming of 1.5, 2, and 3°C, Hydrol. Earth Syst. Sci., 22, 1017–1032, doi:10.5194/hess-22-1017-2018, 2018.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales. In: Proceedings of the 8^{th} Conference on Applied Climatology, Vol. 17, American Meteorological Society Boston, MA, pp. 179–183, 1993.

Mendoza, P. A., Wood, A. W., Clark, E., Rothwell, E., Clark, M. P., Nijssen, B., Brekke, L. D., and Arnold, J. R.: An intercomparison of approaches for improving operational seasonal streamflow forecasts, Hydrol. Earth Syst. Sci., 21, 3915–3935, doi:10.5194/hess-21-3915-2017, 2017.

Mishra, A. K., and Singh, V. P.:A review of drought concepts, Journal of Hydrology, 391, 202-216, https://doi.org/10.1016/j.jhydrol.2010.07.012, 2010.

Mishra, A.K., and Desai, V.R.: Drought forecasting using stochastic models, Stoch. Environ. Res. Ris. Assess., 19, 326–339, https://doi.org/10.1007/s00477-005-0238-4, 2005.

Nalbantis, I., and Tsakiris, G.: Assessment of hydrological drought revisited, Water Resour. Manage., 23, 881-897, doi:10.1007/s11269-008-9305-1, 2009.

Pappenberger, F., Thielen, J., and Del Medico, M.: The impact of weather forecast improvements on large scale hydrology: analyzing a decade of forecasts of the European Flood Alert System, Hydrol. Process., 25, 1091–1113, https://doi.org/10.1002/hyp.7772, 2011.

Pechlivanidis, I. G., Crochemore, L., Rosberg, J., and Bosshard, T.: What are the key drivers controlling the quality of seasonal streamflow forecasts? Water Resources Research, 56, e2019WR026987, https://doi.org/ 10.1029/2019WR026987, 2020.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, 2007.

Peters, E., Bier, G., Van Lanen, H. A. J., and Torfs, P. J. J. F.: Propagation and spatial distribution of drought in a groundwater catchment, J. Hydrol., 321, 257–275, doi:10.1016/j.jhydrol.2005.08.004, 2006.

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

Pfister, C., Weingartner, R., and Luterbacher, J.: Hydrological winter droughts over the last 450 years in the upper Rhine basin: a methodological approach, Hydrological Sciences Journal, 51:5, 966-985, doi:10.1623/hysj.51.5.966, 2006.

Poljanšek, K., Marin Ferrer, M., De Groeve, T., and Clark, I.: Science for disaster risk management 2017: knowing better and losing less, executive summary, EUR 28034 EN, ISBN 978-92-79-60679-3, https://doi.org/10.2788/842809, JRC102482, 2017.

Pozzi, W., Sheffield, J., Stefanski, R., Cripe, D., Pulwarty, R., Vogt, J. V., Heim Jr, R. R., Brewer, M. J., Svoboda, M., Westerhoff, R.,. . . . . ., and Lawford, R.: Toward global drought early warning capability: Expanding international cooperation for the development of a framework for monitoring and forecasting, Bulletin of the American Meteorological Society, 94 (6), 776–785, https://doi.org/10.1175/BAMS-D-11-00176.1, 2013.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Fransses, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, PNAS, vol.111, no.9, 3262-3267, doi:10.1073/pnas.1222473110, 2014.

Prudhomme, C., Parry, S., Hannaford, J., Clark, D. B., Hageman, S., and Voss, F.: How well do large-scale models reproduce regional hydrological extremes in Europe? Journal of Hydrometeorology, 12, 1181-1204, doi:10.1175/2011JHM1387.1, 2011.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., and Marx, A.: Anthropogenic warming exacerbates European soil moisture droughts, Nature Climate Change, 8, 421-426, doi:10.1038/s41558-018-0138-5, 2018.

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

Schaake, J. C., Hamill, T. M., Buizza, R., and Clark, M.: HEPEX: the hydrological ensemble prediction experiment, Bulletin of the American Meteorological Society, 88(10), 1541-1547, 2007.

~~Schneider, C., Laize, C.L.R., Acreman, M.C., and Flörke, M.: How will climate change modify river flow regimes in Europe? Hydrol.~~

Sepulcre-Canto, G., Horion, S., Singleton, A., Carrao, H., and Vogt, J.: Development of a combined drought indicator to detect agricultural drought in Europe, Nat. Hazards Earth Syst. Sci., ~~17, 325~~12, 3519–~~339, doi:~~3531, https://doi.org/10.5194/ ~~hess-17-325-2013, 2013.~~ nhess-12-3519-2012, 2012.

Sivakumar, M. V. K., Stefanski, R., Bazza, M., Zelaya, S., Wilhite, D., and Magalhaes, A. R.: High Level Meeting on National Drought Policy: Summary and Major Outcomes, Weather and Climate Extremes, 3, 126–132, http://dx.doi.org/10.1016/j.wace.2014.03.007, 2014.

Slater, L.J., and Villarini, G.: Enhancing the predictability of seasonal streamflow with a statistical-dynamical approach, Geophysical Research Letters, 45(13), pp.6504-6513, 2018.

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., De Stefano, L., Aca´cio, V., Dias, S., Stagge, J. H., Tallaksen, L. M., Kampragou, E.,. . . . . . , and Van Lanen, H. A. J.: Impacts of european drought events: insights from an international database of text-based reports., Natural Hazards and Earth System Sciences, 16 (3), 801–819, https://doi.org/10.5194/nhess-16-801-2016, 2016.

Stockdale, T., Johnson, S., Ferranti, L., Balmaseda, M., and Briceag, S.: ECMWF's new long range forecasting system SEAS5, Vol. 154. ECMWF Newsletter, doi:10.21957/tsb6n1, 2018.

Sung, J. H., and Chung, E.-S.: Development of streamflow drought severity-duration-frequency curves using the threshold level method, Hydrol. Earth Syst. Sci., 18, 3341–3351, doi:10.5194/hess-18-3341-2014, 2014.

Sutanto, S. J., Van Lanen, H. A. J., Wetterhall, F., and Llort, X.: Potential of pan-European seasonal hydro-meteorological drought forecasts obtained from a Multi-Hazard Early Warning System, Bulletin of the American Meteorological Society, 101, 368-393, https://doi.org/10.1175/BAMS-D-18-0196.1, 2020a.

Sutanto, S. J., Wetterhall, F., and Van Lanen, H. A. J.: Hydrological drought forecasts outperform meteorological drought forecasts, Environ. Res. Lett., 15, 084010, https://doi.org/10.1088/1748-9326/ab8b13, 2020b.

Sutanto, S. J., and van Lanen, H. A. J.: Hydrological drought characteristics based on groundwater and runoff across Europe, Proc. IAHS, 383, 281–290, https://doi.org/10.5194/piahs-383-281-2020, 2020.

Sutanto, S. J., Van der Weert, M., Wanders, N., Blauhut, V., and Van Lanen, H. A. J.: Moving from drought hazard to impact forecasts, Nat. Comm., 10:495, https://doi.org/10.1038/s41467-019-12840-z, 2019.

Tallaksen, L. M., Hisdal, H., and Van Lanen, H. A. J.: Space-time modeling of catchment scale drought characteristics, Journal of Hydrology, 375, 363–372, 2009.

Tallaksen, L. M., and Van Lanen, H. A. J.: Hydrological drought: processes and estimation methods for streamflow and groundwater, In: Developments in Water Science, vol. 48, Amsterdam, the Netherlands: Elsevier Science B.V, 2004.

Tallaksen, L. M., Madsen, H., and Clausen, B.: On the definition and modeling of streamflow drought duration and deficit volume, Hydrological Sciences Journal, 42:1, 15-33, doi:10.1080/02626669709492003, 1997.

Thielen, J., Bartholmes, J., Ramos, M.-H., and Roo, A. D.: The European Flood Alert System - part 1: concept and development, Hydrol. Earth Syst. Sci., 13, 125–140, https://doi.org/10.5194/hess-13-125-2009, 2009.

Tijdeman, E., Stahl, K., and Tallaksen, L. M.: Drought characteristics derived based on the Standardized Streamflow Index: A large sample comparison for parametric and nonparametric methods, Water Resources Research, 56, e2019WR026315, https://doi.org/10.1029/2019WR026315, 2020.

Trambauer, P., Werner, M., Winsemius, H. C., Maskey, S., Dutra, E., and Uhlenbrook, S.: Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa, Hydrology and Earth System Sciences, 19(4), 1695-1711, 2015.

Trambauer, P., Maskey, S., Winsemius, H., Werner, M., and Uhlenbrook, S.: A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa, Physics and Chemistry of the Earth, 66, 16-26, 2013.

Van Der Knijff, J. M., Younis, J., and De Roo, A. P. J.: Lisflood: a gis-based distributed model for river basin scale water balance and flood simulation, International Journal of Geographical Information Science, 24:2, 189–212, https://doi.org/10.1080/13658810802549154, 2010.

Van Der Knijff, J.: LISVAP: Evaporation Pre-Processor for the LISFLOOD Water Balance and Flood Simulation Model, EUR 22639 EN/2, 2008.

Van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R. A. M., Liu, Y. Y., Podger, G. M., Timbal, B., and Viney, N. R.: The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, Water Resources Research, 49, 1040–1057, doi:10.1002/wrcr.20123, 2013.

Van Hateren, T., Sutanto, S. J., and Van Lanen, H. A. J.: Evaluating uncertainty and robustness of seasonal meteorological and hydrological drought forecasts at the catchment scale-case Catalonia (spain), Env. Int., 133, 105206, https://doi.org/10.1016/j.envint.2019.105206, 2019.

~~Van Huijgevoort, M. H. J., Van~~

Van Lanen, H. A. J., ~~Teuling,~~ Wanders, N., Tallaksen, L. M., and Van Loon, A. ~~J. , and Uijlenhoet, R. : Identification of changes in hydrological drought characteristics from a multi-GCM driven ensemble constrained by observed discharge, Journal of Hydrology, 512, 421-434, doi:10.1016~~F.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrol. Earth Syst. Sci., 17, 1715–1732, doi:10.5194/~~j.hydrol.2014.02.060, 2014.~~ hess-17-1715-2013, 2013.

Van Lanen, H. A. J., Fendeková, M., Kupczyk, E., Kasprzyk, A., and Pokojski, W.: Flow Generating Processes, in: Hydrological Drought, Processes and Estimation Methods for Streamflow and Groundwater, edited by: Tallaksen, L. M. and Van Lanen, H. A. J., Development in Water Science 48, Elsevier Science B.V., 53–96, 2004.

Van Loon, A. F., Rangecroft, S., Coxon, G., Naranjo, J. A. B., Ogtrop, F. V., and Van Lanen, H. A. J.: Using paired catchments to quantify the human influence on hydrological droughts, Hydrol. Earth Syst. Sci., 23, 1725-1739, https://doi.org/10.5194/hess-23-1725-2019, 2019.

Van Loon, A. F.: Hydrological drought explained, WIREs Water, https://doi.org/10.1002/wat2.1085, 2015.

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

Van Loon, A. F., Van Huijgevoort, M. H. J., and Van Lanen, H. A. J.: Evaluation of drought propagation in an ensemble mean of large-scale hydrological models, Hydrol. Earth Syst. Sci., 16, 4057-4078, doi:10.5194/hess-16-4057-2012, 2012.

Van Loon, A. F., Fendeková, M., Hisdal, H., Horvát, O., Van Lanen, H. A. J., Machlica, A., Oosterwijk, J., and Tallaksen, L. M.: Understanding hydrological winter drought in Europe, in: ~~6th~~ 6th World FRIEND Conference "Global Change: Facing Risks and Threats to Water Resources", edited by: Servat, E., Demuth, S., Dezetter, A., Daniell, T., Ferrari, E., Ijjaali, M., Jabrane, R., Van Lanen, H. A. J., and Huang, Y., IAHS-AISH P., 340, 189–197, 2010.

Vicente-Serrano, S. M., Lo´pez-Moreno, J. I., Begueri´a, S., Lorenzo-Lacruz, J., Azorin-Molina, C., and Morán-Tejeda, E.: Accurate computation of a streamflow drought index, J. Hydrol. Eng., 17(2), 318-332, doi:10.1061/(ASCE)HE.1943-5584.0000433, 2012.

Vicente-Serrano, S. M., Begueria, S., and López-Moreno, J. I.: A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index-SPEI, Journal of Climate, 23(7), 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M., and Baillon, M.: Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite, Hydrol. Earth Syst. Sci., 14, 459–478, https://doi.org/10.5194/hess-14-459-2010, 2010.

Vogel, R. M., and Stedinger, J. R.: Generalized storage-reliability-yield relationships, J. Hydrol., 89, 303-327, 1987.

Wanders, N., Wada, Y., and Van Lanen, H. A. J.: Global hydrological droughts in the 21^{st} century under a changing hydrological regime, Earth Syst. Dynam., 6, 1-15, 2015.

Wanders, N., Thober, S., Kumar, R., Pan, M., Sheffield, J., Samaniego, L., and Wood, E.: Development and evaluation of a Pan-European multi-model seasonal hydrological forecasting system, Journal of Hydrometeorology, 20, 99-115, 2019.

Wilhite, D. A., Svoboda, M. D., and Hayes, M. J.: Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness, Water Resour. Manage., 21, 763–774,doi:10.1007/s11269-006-9076-5, 2007.

WMO & GWP.: National Drought Management Policy Guidelines: A Template for Action (D. A. Wilhite). Integrated Drought Management Programme (IDMP) Tools and Guidelines Series 1. WMO, Geneva, Switzerland and GWP, Stockholm, Sweden, [https://public.wmo.int/en/resources/library/national-drought-management-policy-guidelines-template-action], 2014.

Wong, W. K., Beldring, S., Engen-Skaugen, T., Haddeland, I., and Hisdal, H.: Climate Change Effects on Spatiotemporal Patterns of Hydroclimatological Summer Droughts in Norway, J. Hydrometeorol., 12, 1205–1220, doi:10.1175/2011JHM1357.1, 2011.

Yevjevich, V.: An objective approach to definition and investigations of continental hydrologic droughts, Hydrology Papers, 23, Colorado State University, Fort Collins, USA, 1967.

Yuan X., Zhang, M., Wang, L., and Zhou, T.: Understanding and seasonal forecasting of hydrological drought in the Anthropocene, Hydrol. Earth Syst. Sci., 21, 5477–5492, doi:10.5194/hess-21-5477-2017, 2017.

~~Yuan, X., and Wood, E. F.: Multimodel seasonal forecasting of global drought onset, Geohpysical Research Letters, 40, 4900-4905, doi:10.1002/grl.50949, 2013.~~

~~Yuan, X., Wood, E. F., Chaney, N. W., Sheffield, J., Kam, J., Liang, M., and Guan K.: probabilistic seasonal forecasting of African drought by dynamical models, Journal of Hydrometeorology, 14, 1706-1720, doi:10.1175/JHM-D-13-054.1, 2013.~~