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Manuscript prepared for Hydrol. Earth Syst. Sci. Discuss.
with version 4.1 of the LaTeX class copernicus_discussions.cls.
Date: 6 May 2015

Investigation of variable threshold level approaches for hydrological drought identification

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Abstract

Threshold level approaches are widely used to identify drought events in time series of hydrometeorological variables. However, the method used for calculating the threshold level can influence the quantification of drought events or even introduce artefact drought events. In this study, four methods of variable threshold calculation have been tested on catchment scale, namely (1) moving average of monthly quantile (M_MA), (2) moving average of daily quantile (D_MA), (3) thirty days moving window quantile (30D) and (4) fast Fourier transform of daily quantile (D_FF). The levels obtained by these methods were applied to hydrometeorological variables that were simulated with a semi-distributed conceptual rainfall-runoff model (HBV) for five European catchments with contrasting catchment properties and climate conditions. There are no physical arguments to prefer one method over the other for drought identification. The only way to investigate this is by applying the methods and visually inspecting the results. Therefore, drought statistics (i.e. number of droughts, mean duration, mean deficit) and time series plots were studied to compare drought propagation patterns determined by different threshold calculation methods. We found that all four approaches are sufficiently suitable to quantify drought propagation in contrasting catchments. Only the D_FF approach showed lower performance in two catchments. The 30D approach seems to be optimal in snow-dominated catchments, because it follows fast changes in discharge caused by snow melt more accurately. The proposed approaches can be successfully applied by water managers in regions where drought quantification and prediction are essential.

1 Introduction

Drought is a hazardous natural event that is associated with below-average water availability in the hydrological cycle due to climate variability. Unlike other natural hazards (e.g. floods), drought has a very complex development pattern (onset, impacted area, severity, recovery) that cannot be easily understood. Drought is often detected after it has already well developed (Wilhite, 2000; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Sheffield and

Wood, 2012). Many regions across the world are vulnerable to drought, leading to immense socio-economic and environmental impacts. In some areas, even fatalities are reported because of drought-related impacts. For example, the 2011 drought in the Horn of Africa resulted in famine and thousands lost lives (Zarocostas, 2011; Hillier and Dempsey, 2012). As reported by Sheffield and Wood (2008, 2012), Wanders et al. (2010), Orlowsky and Seneviratne (2013), Prudhomme et al. (2013), Forzieri et al. (2014), and Van Huijgevoort et al. (2014), drought severity will likely increase in multiple regions across the globe. They also refer to large spread in projections, because of uncertainties in emission scenarios, climate models and in particular large-scale hydrological models. Despite these uncertainties, current and projected impacts urge societies in many regions to explore water futures and solutions through increasing drought vulnerability (e.g. Fischer et al., 2011; Cosgrove and Cosgrove, 2012; Gallopín, 2012). Adaptive management strategies (e.g. ~~Holling et al., 1978~~ **Holling , 1978**) are anticipated to frame operational and long-term drought management, including identification of promising measures, and water-related policy making.

The impacts of past and future drought are also uncertain because of definitional issues (e.g. Seneviratne et al., 2012), which hamper vulnerability and adaptation studies. Different drought types need to be distinguished, because characteristics (e.g. frequency, duration, deficit volumes) substantially differ between meteorological drought (precipitation deficit), soil moisture drought and hydrological drought (below-normal groundwater or river flow) due to drought propagation through the subsurface part of the water cycle (e.g. Peters et al., 2003; Van Loon and Van Lanen, 2012). Different identification methods that are used for a specific drought type are another source of uncertainty (e.g. Sheffield et al., 2012). Two main groups of identification methods are usually applied, which have in common that long time series of hydrometeorological data are required (preferably 30 years or longer). The first group is based on the probability of an observed hydrometeorological variable occurring over a given prior period. It provides the deviation from normal (drought severity) in terms of ~~SD~~**standard deviation**. The most well-known is the Standardized Precipitation Index, SPI (McKee et al., 1993). Others are developed for soil moisture (SMA; Sheffield et al., 2004); groundwater (GRI; Bloomfield and Marchant, 2013), and river flow (SRI; Shukla and Wood, 2008). The second widely applied group is the threshold approach: a drought occurs when the hydrometeorological variable is below a predefined threshold. ~~The threshold method was introduced by Yevjevich (1967).~~ **The drought event definition by Yevjevich et al. (1983) was originally developed for analysing time series with a time resolution of one month or longer. Because droughts develop slowly and are a so-called "creeping disaster" (Wilhite, 2000), a monthly time resolution might be sufficient to quantify drought characteristics. The disadvantage, however, is that calender months are an arbitrary subdivision of the year and the timing of a discharge peak strongly influences whether a month is classified as dry or wet. Therefore, a daily resolution is advised also for drought studies. The threshold level method of Yevjevich et al. (1983) was successfully tested on daily hydrographs (Zelenhasić and Salvai, 1987; Tallaksen et al., 1997; Kjeldsen et al., 2000; Tate and Freeman, 2000; Hisdal et al., 2001).** Hisdal et al. (2004), Fleig et al. (2006), Mishra and Singh (2010), and Sheffield and Wood (2012) provide overviews for application of this approach to drought analysis.

The choices made in the implementation of the threshold method, including the selection of the threshold level, are crucial. Ideally, the threshold level should be defined by drought impacted sectors, e.g. irrigated agriculture, cooling water for energy plants, drinking water supply, reservoir operation levels, navigation depth, or environmental flows to support stream ecology (Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Sheffield and Wood, 2012). Either a fixed or a variable (seasonal, monthly or daily) threshold can be used (Hisdal et al., 2004). A fixed threshold, for example, is relevant to study ecological minimum flows. A variable threshold is more appropriate when seasonal patterns need to be taken into account; e.g. anomalies in groundwater recharge during the wet season are more important for groundwater resource management than focus on the dry season when recharge under normal conditions already is low or non-existing. A variable threshold approach has been used in many hydrological drought studies, e.g. Stahl (2001), Nyabeze (2004), Hirabayashi et al. (2008), Vidal et al. (2010), Hannaford et al. (2011), Prudhomme et al. (2011), Parry et al. (2012), Van Loon and Van Lanen (2013), Van Lanen et al. (2013), Van Huijgevoort et al. (2013), Wada et al. (2013), Forzieri et al. (2014), and Wanders et al. (2014). **The most straightforward application of a variable threshold is the use of a monthly threshold on data with a monthly resolution**

(e.g., Mathier et al., 1992; Lehner et al., 2006; Weiß et al., 2007; Van Huijgevoort et al., 2012; Wada et al., 2013).

~~A number of studies use a variable threshold method that is based on post-processing of long-term average monthly flow, which was introduced by Van Loon et al. (2010). When applying the variable threshold method, Van Loon and Van Lanen (2012) found artefact drought events in some catchments, i.e. short-lived events with usually a high water deficit.~~ **The question arises how to determine the variable threshold level for hydrological drought analyses on daily time scale. Applying 30-days moving average threshold level to daily data, Van Loon and Van Lanen (2012) found artefact drought events in some catchments, i.e. short-lived events, associated with the staircase pattern of monthly thresholds**. These artefact events were not caused by weather anomalies (precipitation, temperature), but likely by the way the variable threshold had been implemented. The artefact events appeared when the flow increased very quickly (e.g. transition between winter low-flow period and the snow melt peak) in connection with a gradually increasing threshold level. This also might explain the short-lasting, but substantial increase in the global area in drought around March-April (which is the snow melt season on the Northern Hemisphere), as reported by Corzo Perez et al. (2011). The identified artefact drought events are of no or little relevance for possible drought-impacted sectors, because of their short duration and per definition high flows afterwards. This indicates that the current implementation of the threshold based on post-processed smoothed monthly values seems not be most suitable all around the world. **The same threshold level is used in this paper as M_MA threshold level approach.**

Another option is using a daily threshold. Zaidman et al. (2002) use standardised daily anomalies, which are comparable to a daily threshold, and Fleig et al. (2011) use a daily threshold. In both studies, the daily values were not smoothed to produce reliable threshold levels. This is not problem for observations or simulations with a very long period of record, in which extreme daily values are averaged out. For short periods of record, however, it leads to a threshold level in which extreme daily values have a big influence, because not enough observations are available to create a smooth duration curve. Smoothing of the daily threshold with a moving average (D_MA in this study) has, to our best knowledge,

never been used before. Smoothing the daily threshold can also be done by a Fourier transform (in this study D_FF). The advantage is that it is a global method, which takes into account the total pattern instead of only the values just before and after the target value. To our knowledge a variable threshold level calculated with use of a Fourier transform has never been applied before. Instead of performing a smoothing afterwards (like in M_MA, D_MA, and D_FF), smoothing can also be incorporated in the calculation of the threshold itself. In that case, the threshold is not based on calender months, not on daily values, but on a moving window of a number of days. In this study, we used a moving window of 30 days (30D), while in other studies moving windows of 11 days (Stahl, 2001), 21 days (Hirabayashi et al., 2008) and 30 days Hannaford et al. (2011); Prudhomme et al. (2013) were used. Stahl (2001) investigated the sensitivity for the period of the moving window and concluded that differences start to level off around the 10 day **window.**

The aim of this paper is to systematically analyse the ~~performance of four different methods for implementation of the variable threshold~~ **sensitivity of drought characteristics to four different threshold level calculation methods** to identify hydrological droughts in different geoclimatic conditions. The paper starts with presenting the main characteristics of five contrasting catchments in Europe (Sect. 2) that were used to test the methods, followed by a description of the basics of the four methods to implement the variable threshold method (Sect. 3). The results are presented in the form of general drought characteristics, which are complemented with selected drought event to illustrate similarities and differences for the different methods and catchments (Sect. 4). The results are discussed in light of the drought identification in different geoclimatic settings at different scales (Sect. 5). Finally, the conclusions are given in Sect. 6.

2 Study area

The study areas of this research are five European catchments that are headwaters of basins with contrasting catchment characteristics and climate conditions (Van Loon and Van Lanen, 2012). These catchments are the Narsjø catchment (south-eastern Norway), Upper-Metuje catchment (north-eastern Czech Republic and partly in Poland), Upper-Sázava catchment (central Czech Republic), Nedožery catchment (central Slovakia), and Upper-Guadiana catchment (central Spain) (Fig. 1). The catchments can be considered as representative of different climatic zones and diverse environmental conditions in Europe; from subarctic climate with very high inter-annual temperature and snow-cover variation to semiarid climate with greater potential evapotranspiration and extended groundwater system (Van Lanen et al., 2008; Van Loon, 2013). ~~Therefore, the results of investigating the variable threshold levels could be applicable to drought analysis in other catchments around the world, where observed and/or simulated hydrometeorological data are available.~~ Van Loon and Van Lanen (2012) simulated the hydrometeorological variables from observations using the conceptual, semi-distributed rainfall-runoff model, HBV (Seibert, 2000). They took the observed precipitation and temperature from stations inside and around the catchment, calculated catchment average values using the Thiessen polygon method, and corrected for elevation. In addition, they calculated potential evapotranspiration using the adapted Penman–Monteith method (Doorenbos and Pruitt, 1975; Allen et al., 1998).

Daily local forcing data, i.e. precipitation, potential evapotranspiration, and temperature, were used as an input for HBV model to simulate daily soil moisture, groundwater storage and discharge. Van Loon and Van Lanen (2012) used the Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970) based on the logarithm of discharge as criterion to verify the model's performance to simulate the observed discharge. The model performance for these five catchments was between 0.63 and 0.9, which was generally taken as satisfactory or above (Van Loon and Van Lanen, 2012). ~~The model outputs were used in this research.~~ **The results of these model simulations were exclusively used in this study for analysing the sensitivity of drought characteristics to different threshold level approaches. The HBV model was tested for catchments from all over the world and has proven to generate hydrometeorological variables required for drought propagation analysis with reasonable performance (Van Loon Van Lanen, 2012). Therefore, we expect that applying the proposed approaches to basins worldwide with little or no pronounced seasonality would bring little difference between the approaches.**

3 Methodology

The variable threshold level should represent the low-flow regime of a catchment. Therefore, the optimum calculation method is a daily quantile based on very long time series to average out intra-annual variation. Often such long time series are not available and threshold levels have to be calculated from shorter time series introducing variability in the regime curve and, therefore, in the threshold level.

There are several possibilities to create a smooth threshold level when time series are not long enough. One option is smoothing the daily threshold levels. Another approach is the use of monthly data for calculation of the threshold. These two approaches are based on two consequent steps, namely a basic threshold level calculation and a smoothing procedure. The smoothing can be done in various ways, subdivided in local and global methods. A local method, like moving average, takes into account the data close to the data point under consideration, whereas a global method, like Fourier transform, takes into account the entire dataset. The third approach combines the two steps of basic threshold calculation and smoothing into one procedure.

In this study, thresholds have been calculated for the hydrometeorological variables; precipitation, soil moisture storage, groundwater storage and discharge. We applied the threshold calculation and the smoothing techniques to these variables as discussed below. The variables are denoted as Q_{i_j} for quantile series and Thr_{i_j} for the calculated threshold level, where i stands for the ~~methods of~~ threshold calculation **method**, i.e. daily (D), monthly (M), moving window of 30 days (~~D30~~**30D**), and j stands for the subsequent smoothing techniques, i.e. moving average (MA) and fast Fourier (FF) transform. **In all of the four approaches, the threshold level was calculated on the daily basis for 364 days. We removed hydrometeorological data corresponding to 29th of February each year as we have the required data for this date only once in four years. The threshold calculation takes into account only the 28 days of this month throughout the observation period. In addition, we only applied thirty-days moving window quantile to temperature and snow accumulation time series and used the same threshold level in other approaches when analysing drought propagation patterns.**

3.1 Moving average of monthly quantile (M_MA)

In this approach, the basic calculation of the threshold was done based on the cumulative distribution of ~~long-term~~ monthly data. The threshold level was calculated as the 80th percentile of the flow duration curve of this distribution.

$$Q_{\mathrm{M\_MA}}(n) = \mathrm{quantile}(\mathrm{month} == \mathrm{month}[n]) \tag{1}$$

where $Q_{\mathrm{M\_MA}}(n)$ is the exceedance threshold level of the nth month of the calendar year.

The calculated exceedance threshold was assigned as the threshold level for each day of the month. This resulted in a fixed threshold level for this predefined month. The annual curve of threshold levels is, therefore, produced from 12 blocks of monthly threshold levels. When confronting time series of daily data with monthly threshold levels, jumps between two consecutive months resulted in unrealistic drought behaviour that extends around the beginning and end of each month. This is because of the difference between slowly-changing actual time series and sudden jumps in the threshold level at the interface of the two months. This requires the use of smoothing technique to get a reliable threshold level that avoids such unrealistic drought behaviour. Therefore, we applied 30 days centred moving average to these discrete monthly thresholds as follows:

$$\mathrm{Thr}_{\mathrm{M\_MA}}(m) = \mathrm{average}(Q_{\mathrm{M\_MA}}[m-14] : Q_{\mathrm{M\_MA}}[m+15]) \tag{2}$$

where $\mathrm{Thr}_{\mathrm{M\_MA}}(m)$ is the threshold level of the mth day of the calendar year calculated from moving average of 30 consecutive days with monthly quantiles (Fig. 2).

3.2 Moving average of daily quantile (D_MA)

The first step in this approach was to compute daily quantiles from cumulative distribution of hydrometerological data through the entire observation period. Therefore, we created 365 flow duration curves from which 365 threshold levels were determined. We calculated the 80th percentile as the exceedance threshold from the calender daily cumulative distribution as:

$$Q_{\mathrm{D\_MA}}(m) = \mathrm{quantile}(\mathrm{day} == \mathrm{day}[m]) \tag{3}$$

where $Q_{\mathrm{D\_MA}}(m)$ is the daily quantile of the mth day of the calendar year.

However, the time series of the daily thresholds gave a fluctuating threshold level that led to frequent and short-lived deficit periods that could not be identified as drought (Fig. 2). Therefore, we implemented the smoothing techniques of a centred moving average of 30 days as (similar to the previous threshold level method):

$$\mathrm{Thr}_{\mathrm{D\_MA}}(m) = \mathrm{average}(Q_{\mathrm{D\_MA}}[m-14] : Q_{\mathrm{D\_MA}}[m+15]) \tag{4}$$

where $\mathrm{Thr}_{\mathrm{D\_MA}}(m)$ is the threshold level of the mth day of the calender year calculated using D_MA threshold method.

3.3 Thirty-days moving window quantile (30D)

In this approach, daily threshold levels were calculated based on quantiles from flow duration curve over a ~~monthly~~ **30 days** time window that moves through the time series. Therefore, the distribution was made on a monthly basis, however, without taking calendar months as a starting point. This was done until annual curves of daily thresholds were attained, which give a threshold level that does not necessarily require additional smoothing (Fig. 2).

$$\mathrm{Thr}_{\mathrm{30D}}(m) = \mathrm{quantile}(m-14 \leq \mathrm{day} \leq m+15) \tag{5}$$

where $\mathrm{Thr}_{\mathrm{30D}}(m)$ is the threshold level of the mth day of the year calculated using 30D threshold level method.

3.4 Fast Fourier transform approach (D_FF)

Any time series signal that is represented by non-periodic functions (for example, time series of precipitation or discharge) can be approached as a linear sum of many discrete sinusoidal frequency components. These discrete frequencies can be obtained using Fourier

Transform; the method that converts the time series data into frequency components. For discrete time series signal data, the conversion is done by using large number of complex multiplications. Fast Fourier Transform uses special algorithm that accelerates the conversion process by reducing the number of such multiplications (Kimball , 1974; Knuth , 1998; Johnson and Frigo , 2007).

The conversion enabled us to apply piecewise mathematical manipulations such as attenuation and removal on the frequency components above a predefined frequency called cut-off frequency. The cut-off frequency was optimized until the inverse Fourier Transform the frequency signal best fitted the 30D threshold level. We chose this threshold level for optimization because it does not require secondary smoothing (quantile calculation followed by application of smoothing techniques). This manipulation resulted in smoothed spectrum and when inverse Fourier Transform was applied, it provided smooth time series signal (smoothed time series of hydrometeorological variables). We named this intra-annual variable threshold as the D_FF threshold level.

In ~~this~~ **D_FF threshold level** approach, we used the annual curve of the daily thresholds determined using the basic calculation method **that is similar to the calculation technique we** applied in the second threshold level method (Eq. 3).

$$Q_{\mathrm{D\_FF}}(m) = \mathrm{quantile}(\mathrm{day} == \mathrm{day}[m]) \qquad (6)$$

where $Q_{\mathrm{D\_FF}}(m)$, in this approach, is the threshold level of the mth day of the calendar year calculated using D_FF threshold level method.

The fast Fourier transform assumes that this data contains a set of repeating daily measurements. The time series of hydrometeorological variables was, therefore, converted to frequency series, which was then modified by removing Fourier components with frequencies higher than a cutoff frequency. ~~The cutoff frequency is optimized in such a way that the inverse of the modified frequency series best fits the time series of the threshold level determined by 30D threshold level method.~~

$$\mathrm{Thr}_{\mathrm{D\_FF}}(m) = \mathrm{FFT}(Q_{\mathrm{D\_FF}}) \qquad (7)$$

where FFT is the fast Fourier transform algorithm applied on the mth day quantile ($Q_{\mathrm{D\_FF}}$) and $\mathrm{Thr}_{\mathrm{D\_FF}}(m)$ is the corresponding daily threshold level determined using D_FF threshold level method.

The results of the threshold calculation methods applied to the Narsjø catchment (Norway) are displayed in Fig. 2. **The figure displays intra-annually variable daily quantile series determined using basic calculation (represented by thin solid line) compared to the same quantile series as smoothed by different approaches (marked with broken lines.** When we systematically analyse the behaviour of the threshold level approaches through each hydrological regime, it seems that the methods perform differently during the high-flow period (from May to July). For example, the M_MA threshold is well below the discharge curve during the high-flow period. The D_FF threshold, however, seems to be very close to the actual discharge curve.

In addition, Fig. 2 displays strange oscillations during January to May low-flow periods that is caused by the Fourier transform. It uses sin-functions to fit the snow-melt peak, but then applies the same sin-functions to the winter low-flow period as it takes the global dataset (entire dataset of a variable from the catchment) during transformation between time series to frequency series of the variable.

3.5 Computation of drought characteristics

The calculated threshold levels were applied to the entire time series of all catchments. The ~~magnitudes~~**amount** of drought characteristics were computed based on the difference ~~of~~**between** the actual time series **(i.e. the amount of the daily simulated variable for a particular day and year in the past)** and ~~the~~**it's** threshold level. **We followed well-established procedure in drought research to calculate the required characteristics. We first minimized the dependency between two or more events by applying a pooling procedure based on an inter-event period of 10 days (Tallaksen et al., 1997; Fleig et al., 2006)**. ~~The use of threshold level at daily temporal resolution introduces minor drought events and possible dependency between two or more consecutive drought events (Hisdal, 2002; Hisdal, 2012). To remove minor drought events, we excluded events that persisted for less than 15 days, as~~

~~suggested by Hisdal et al. (2004), Fleig et al. (2006), and Van Loon et al. (2011) (Fig. 3). To eliminate dependencies, we applied a pooling procedure based on an inter-event period of 10 days (Tallaksen et al., 1997; Tallaksen et al., 2006).~~ With this procedure, two consecutive drought events with drought duration (D_i and D_{i+1}) and deficit volume (V_i and V_{i+1}) and with an inter-event period (t_c) less than 10 days were pooled together as follows to generate the jth drought event.

$$D_{\text{pooled}}(j) = D_i + D_{i+1} + D_{i+\mathbf{2}} + \cdots \tag{8}$$

$$V_{\text{pooled}}(j) = V_i + V_{i+1} + V_{i+2} + \cdots \tag{9}$$

where $D_{\text{pooled}}(j)$ is the drought duration of the jth drought event and $V_{\text{pooled}}(j)$ is its deficit volume.

For state variables, the maximum deviation from the threshold level was used as a severity measure (H). For these variables, deficit volume (V_{pooled}) was replaced by H_{pooled}:

$$H_{\text{pooled}}(j) = \text{Max}(H_i, H_{i+1}, H_{i+2} + \cdots) \tag{10}$$

This procedure was followed by elimination of minor droughts. The use of threshold level at daily temporal resolution introduces minor drought events (Hisdal, 2002; Van Loon and Van Lanen, 2012). To remove these events, we excluded events that persisted for less than 15 days, as suggested by Hisdal et al. (2004), Fleig et al. (2006), and Van Loon et al. (2011) (Fig. 3). Therefore, minor droughts were excluded among the independent drought events.

4 Results

We compared the effect of the threshold calculation approaches on the drought propagation patterns based on the results of qualitative (time series plots) and quantitative (number of droughts, mean duration and deficit volume) analysis of drought. The inter-comparison also included an in-depth analysis of how meteorological drought gives rise to the soil moisture and hydrological droughts upon applying each threshold method. This is because there is no validation with real-time observation, as there is no true method for drought calculations. The analysis was done in two steps: evaluation of drought statistics (Sect. 4.1) followed by visual inspection of the drought propagation pattern (Sect. 4.2).

4.1 General drought statistics

~~It is hypothesized that drought numbers should decrease, mean drought duration should increase and drought severity should decrease moving from meteorological drought through soil moisture drought to hydrological drought.~~

We made intercomparisons of at least 20 cases (5 catchments and 4 variables) and counted the number of times the minimum and maximum values of drought characteristics were identified. For example, we expect four cases (each representing precipitation, soil moisture, groundwater and discharge) for each catchment and becomes 20 cases when repeated for five catchments. We then counted how often (for example, x out of 20) a particular threshold method provided the lowest number of drought, shortest mean duration, lowest deficit volume. This was repeated for the highest number times maximum values of characteristics were identified. In some circumstance, these values may be counted two or three times because two or more threshold levels may have the same lowest or highest values of a particular variable. For example, the number of droughts for Nedoery catchment is 43 when using three threshold methods (M_MA, D_MA and 30D) and 44 (with D_FF). In such circumstances, the number of cases was assumed to be more as we counted these lowest or highest values independently for comparison purposes.

When comparing the threshold level approaches used in this study, D_FF and D_MA threshold methods have rarely given the lowest number of droughts; 1 and 2 times in 26 cases, respectively. However, such number of droughts were often identified when using 30D threshold level approach (in 16 out of 26 cases). On the other hand, the highest number of droughts were often identified when using D_FF threshold level. The method provided the highest number of droughts in 15 out of 22 cases.

~~Comparing the threshold level approaches, the M_MA threshold method has given the least number of droughts in most catchments (Table 1). Except for precipitation and groundwater droughts in the Narsjø catchment, the method produced fewer or a comparable number of~~

~~droughts in all catchments. For example, fewer discharge droughts are identified in the Narsjø catchment, because the calculated threshold level is well above the daily quantiles during periods when abrupt increase in the actual data is confronted by slow rise in the threshold series. This higher threshold level merges two or more droughts together in these periods that could otherwise fall into separate droughts upon using the other three methods. Therefore, the method generates longer mean drought duration. This effect is also noticeable in slow responding catchments such as Upper Metuje and Upper Guadiana.~~

The other drought characteristics we intercompared is the number of times the shortest and longest mean duration were computed. We can see from Table 1 that the shortest mean durations were often identified by D_FF threshold level approach (in 9 out of 20 cases) and the longest ones were identified by D_MA threshold level approach (in 8 out of 20 cases). Figures representing deficit volume may sound insignificant. However, the cumulative deficit over a large catchment area or over an extended period could have a vital implication drought development and recovery processes. Similarly, we also compared the severity of drought characteristics in terms of mean deficit volume. The least severe drought events were often counted when applying the M_MA threshold level (in 10 out of 20 cases); while most severe drought events were often identified when using the D_MA (in 9 of 20 cases) and D_FF (in 8 of 20 cases) threshold level approaches. However, no substantial difference between approaches is found in calculating the magnitudes of discharge deficit for the Guadiana catchment, groundwater deficit in the Nedožery catchment and soil moisture deficit in the Narsjø catchment. Among the drought characteristics, deficit volume is more reliably calculated using all the methods than the number of droughts and mean drought duration.

As can be understood from the above discussion, the difference between frequency of occurrence is most pronounced in the number of droughts. However, there are also such differences between actual drought characteristics as calculated by the four approaches. Some of these examples are number of discharge droughts in Narsjø catchment and precipitation in Upper Sázava catchment, mean groundwater and discharge droughts in Upper-Metuje catchment and precipitation drought deficit in Upper Sázava catchment.

However, the most pronounced deviation is identified in mean groundwater drought duration in the Upper Guadiana catchment. ~~For example~~ In this particular case, the M_MA threshold level approach ~~applied to Upper Guadiana catchment provided average~~ **alone generated mean** groundwater drought duration of ~~130~~**140** days~~, which is~~ longer than the **average of** mean duration computed using the other three threshold approaches **applied to Upper Guadiana catchment (i.e. average of 614, 620 and 614 days)**. This method ~~has~~ resulted in ~~a SD~~ **standard deviation** of 70**.2** days duration among the four threshold methods (Table 2). ~~This effect could be accompanied by the slow response to meteorological droughts in these two catchments caused by an extended aquifer system. Time series of discharge of catchments with extended aquifer systems are much smoother than those of precipitation. Therefore, applying the M_MA smoothing technique to the already smooth time series results in longer drought duration than one would expect.~~ **This increased deviation is attributed to the nature of threshold level in that it stays well above the daily quantile series during extended low-flow periods. Such low-flow periods in the groundwater level are linked to slow response of the catchment to meteorological fluctuations due to large storage in the extended aquifer system and high potential evaporation in the case of Upper Guadiana catchment. In such cases, M_MA threshold level merges two or more groundwater droughts together during these periods that could otherwise fall into separate droughts upon using the other three methods.**

In addition, the threshold levels calculated with the D_FF method have reduced to fixed threshold level **in 3 out of 20 cases** (discharge in Upper-Metuje catchment and precipitation and discharge in Upper Sázava catchment). As a result, the computed mean drought duration for these hydrometeorological variables is much longer than those computed with other methods for the rest of the catchments. For example, ~~for the drought event in 1976~~ the **mean** duration of the discharge drought **in the Upper Sázava catchment** was calculated to be 56 days (from 22 July 1976 to 16 September 1976) when using the M_MA and 30D threshold level methods and 60 days (from 18 July 1976 to 16 September 1976) when using the D_MA threshold level method. However, the same drought was found to sustain for 129 days (from 8 July 1976 to 14 ~~September~~**November** 1976) when applying the D_FF threshold level method. ~~Mean calculated deficit volume is often higher when using the D_FF and D_MA threshold methods~~

~~than using the M_MA and D30~~**30D** ~~threshold methods. However, no substantial difference between approaches is found in calculating the magnitudes of discharge deficit for the Guadiana catchment, groundwater deficit in the Nedožery catchment and soil moisture deficit in the Narsjø catchment. Among the drought characteristics, deficit volume is more reliably calculated using all the methods than the number of droughts and mean drought duration.~~

Despite considerable differences in magnitudes of the drought characteristics, the drought propagation patterns determined with all methods meet our expectations. In all threshold approaches used in this study, larger number of short-lived precipitation droughts propagated into fewer, but prolonged and less severe soil moisture and hydrological droughts (Table 1). ~~To see why the magnitudes differ so much, we need to study drought propagation in more detail by a visual investigation of time series.~~

4.2 Selected drought events

In this section, we ~~identified and~~ presented examples of the most apparent differences and similarities based on the associated drought identification and typology proposed by Van Loon and Van Lanen (2012).

The most important element is the development of some artefact events that were exclusively caused by the chosen method. For example, the M_MA and D_FF threshold level methods have produced artefact drought event in discharge for the Narsjø catchment during **the period of April**~~December 1984~~ to June 1985 without any meteorological drought in the preceding period (Fig. 4). In this particular ~~example~~**period**, the artefact event that persisted for ~~48~~**24** days when using M_MA threshold level method did not appear when we used the 30D threshold method. Such artefact events were successfully removed by 30D threshold approach because it follows the regime more closely (Fig. 2).

The other difference between the threshold level approaches is that the D_FF threshold, in some cases, reduced to a fixed threshold. This significantly impacted the magnitude and severity of some droughts particularly during periods of *classical rainfall deficit drought* (Fig. 5) and *warm snow season drought* (Fig. 6). In such circumstances, the D_FF threshold method gives intense and prolonged droughts that may not be equivalently reproduced by other methods.

For the rest, all threshold level methods performed equivalently in terms of drought propagation patterns. The most pronounced similarity is shown in the example of a *wet-to-dry-season drought* in the Upper Guadiana catchment (Fig. 7). In such circumstances, the impact of the threshold level approaches on the drought propagation pattern is limited to only small changes in duration and deficit volume of these drought events. Similarly, the four threshold level approaches applied to a *rain-to-snow-season drought* event in the Narsjø catchment (Fig. 8) generated drought propagation patterns that only differed in magnitude. In such circumstances, the deviation in the time series of discharge anomalies plays a typical role in the choice for a suitable threshold level approach. In this example, the discharge anomaly persisted for 308 days since 7 March 1976 using the M_MA threshold level method. Similarly, with the 30D approach the anomaly started on the same date but ceased only 3 days earlier. However, the total deficit volume during this period differs from 69 mm (with M_MA) to 58 mm (with 30D threshold level method). **Small breaks can be viewed from Figure 8 during this period because of the fact that the Figure displays the threshold level counterplotted with the daily simulated data before any modification (pooling dependent droughts together and removing minor droughts among independent ones). Such breaks and minor droughts may also appear in other figures. These breaks and minor droughts were taken into account in calculating the drought statistics (Table 1; number of droughts, mean duration and deficit volume). In this particular example, consecutive drought events in discharge were separated by less than 10 days and, therefore, we pooled them together and provided discharge anomaly that persisted for 308 days.** ~~In catchments like the Narsjø catchment, the 30D approach seems to be more reliable than the other three approaches.~~

5 Discussion

~~A variable threshold has been used in many drought studies. The most straightforward application of a variable threshold is the use of a monthly threshold on data with a monthly resolution (e.g., Mathier et al., 1992; , 2006; , 2007; , 2012; , 2013). The drought event definition by Yevjevich et al. (1983) was originally developed for analysing time series with~~

~~a time resolution of one month or longer. Because droughts develop slowly and are a so-called "creeping disaster" (Wilhite, 2000), a monthly time resolution might be sufficient to quantify drought characteristics. The disadvantage, however, is that calender months are an arbitrary subdivision of the year and the timing of a discharge peak strongly influences whether a month is classified as dry or wet. Therefore, a daily resolution is advised also for drought studies. The threshold level method of Yevjevich et al. (1983) was successfully tested on daily hydrographs (Zelenhasić and Salvai, 1987; Zelenhasić and Salvai, 1997; Zelenhasić and Salvai, 2000; Zelenhasić a~~

~~The question arises how to determine the variable threshold level for hydrological drought analyses on daily time scale. A monthly threshold confronted with daily data introduces problems with the "staircase" pattern of the threshold. Therefore, smoothing of the monthly values was done by Van Loon et al. (2010), resulting in a threshold similar to the M_MA threshold level used in this study. This M_MA threshold approach was afterwards used by Corzo Perez et al. (2011), Van Loon and Van Lanen (2012, 2013), Wong et al. (2013), Van Lanen et al. (2013), Van Loon et al. (2014), and Wanders et al. (2014).~~

~~Another option is using a daily threshold. Zaidman et al. (2002) use standardised daily anomalies, which are comparable to a daily threshold, and Fleig et al. (2011) use a daily threshold. In both studies, the daily values were not smoothed to produce reliable threshold levels. This is not problem for observations or simulations with a very long period of record, in which extreme daily values are averaged out. For short periods of record, however, it leads to a threshold level in which extreme daily values have a big influence, because not enough observations are available to create a smooth duration curve. Smoothing of the daily threshold with a moving average (D_MA in this study) has, to our best knowledge, never been used before.~~

~~Smoothing the daily threshold can also be done by a Fourier transform (in this study D_FF). The advantage is that it is a global method, which takes into account the total pattern instead of only the values just before and after the target value. To our knowledge a variable threshold level calculated with use of a Fourier transform has never been applied before.~~

~~Instead of performing a smoothing afterwards (like in M_MA, D_MA, and D_FF), smoothing can also be incorporated in the calculation of the threshold itself. In that case, the threshold is not based on calender months, not on daily values, but on a moving window of a number~~

~~of days. In this study, we used a moving window of 30 days (30D), while in other studies moving windows of 11 days (Stahl, 2001), 21 days (Hirabayashi et al., 2008) and 30 days Hannaford et al. (2011); Hannaford et al. (2013) were used. Stahl (2001) investigated the sensitivity for the period of the moving window and concluded that differences start to level off around the 10 day window.~~

It is hypothesized that drought numbers should decrease, mean drought duration should increase and drought severity should decrease moving from meteorological drought through soil moisture drought to hydrological drought. This implies that large number of meteorological droughts propagate into fewer, prolonged, and less severe soil moisture and hydrological droughts. Differences between the precipitation time series and it's threshold levels are always larger than those for soil moisture, groundwater and river flow. This is because precipitation fluctuates more than soil moisture, groundwater and river flow. Therefore, the drought severity expressed as deficit volume is larger in the precipitation than any of the soil moisture, groundwater or river flow.

In addition to examining our hypothesis, we also performed a rigorous drought propagation analysis in terms of the sensitivity of drought characteristics (number of droughts, mean duration and deficit volume) to different threshold approaches. We applied the proposed threshold approaches to these variables derived from the five selected catchments. We then intercompared how often lowest or highest value of magnitudes of drought characteristics were identified under these methods.

A separate sensitivity analysis of threshold level on drought characteristics should be supported by cumulative effect of threshold levels approaches on drought propagation. Therefore, we looked at how large number of meteorological droughts propagates into fewer, but prolonged and less severe soil moisture and hydrological droughts. Despite substantial differences in magnitudes of the drought characteristics, the drought propagation patterns determined with all methods meet our expectations. In all threshold approaches used in this study, larger number of short-lived precipitation droughts propagated into fewer, but prolonged and less severe soil moisture and hydrological droughts (Table 1). To

see why the magnitudes differ so much, we need to study drought propagation in more detail by a visual inspection of time series of the variables.

In summary, various methods for calculating variable thresholds are available and applied in drought studies. This study is the first to compare different approaches and quantify the differences for a number of contrasting catchments in Europe. The positive conclusion of this study is that all approaches can be used in drought propagation analysis; in general, the same drought propagation patterns were found. This contradicts the common expectation that the choice of the threshold level is extremely important for the outcomes of a drought study (Lehner et al., 2006). It is true that the type (fixed of variable) and magnitude (based on the 70th or 90th percentile) of a threshold changes the values of the drought characteristics, but the effects on drought propagation processes (or changes of drought in the future) are expected to be less influenced, because in those cases relative differences are compared. An exception are future regime changes that are evaluated with a variable threshold. For example, unexpected shift of the snow melt peak in the future will result in high flow during the historical low-flow period (winter) and drought during the historical high flow period (spring) (Van Huijgevoort et al., 2014). Wanders et al. (2014), therefore, proposed a changing threshold for the future.

We also found some discrepancies between the results of the threshold level methods. Largest differences were found in catchments and variables for which the Fourier transform (D_FF) could not characterise the low-flow regime correctly and reduced to a fixed threshold. Additionally, differences were found in catchments with an abrupt change in discharge, e.g. due to snow melt. The 30D and D_FF threshold approaches seemed to capture this fast transition best. As such an abrupt change in discharge might also occur in other climates, for example monsoon climates, the 30D and D_FF level methods seem to be most suitable for global scale drought analysis.

6 Conclusions

In this research, we proposed variable threshold level approaches for hydrological drought identification; namely moving average of monthly quantile (M_MA), moving average of daily quantiles (D_MA), thirty days moving window quantile (30D) and fast Fourier transform of daily quantile (D_FF). We used these threshold level **approaches** ~~determined with these methods to analyse hydrological drought on a daily basis~~ **to systematically analyse the sensitivity of drought characteristics to the proposed approaches in identifying hydrological droughts on daily basis in different geoclimatic conditions. We presented particular cases as displayed in Figures 5-7, where these sensitivities are clearly viewed. We also found that such identification is important for drought typology as there are apparent differences in magnitude and severity of the same drought type but determined by different threshold level approaches.**

We found that the choice of the threshold level approach affects the drought characteristics (in terms of number of droughts, mean duration and deficit volume), but does not significantly affect the drought propagation pattern on which the typology is based. ~~We found that the proposed threshold level approaches are good alternatives for drought propagation analysis and classification.~~ However, the 30D threshold level approach can be preferably used in most catchments, particularly in snow-dominated catchments. This threshold level approach eliminates artefact events that are solely caused by a sharp increase in daily discharge due to sudden snow melt in combination with gradual increase of the threshold level.

The six drought types of Van Loon and Van Lanen (2012) were reproduced using these threshold determination methods. Therefore, the proposed threshold level approaches can be alternatively used in drought propagation analysis and classification. Based on a qualitative analysis of time series of drought events, we concluded that drought propagation patterns are more or less similar irrespective of the threshold level approach implemented. **The proposed threshold level approaches were able to develop drought propagation patterns that clearly illustrate how frequent and severe meterological droughts propagate into fewer, prolonged, and less severe soil moisture and hydrological droughts.** ~~The six drought types of Van Loon and Van Lanen (2012) were reproduced using these threshold determination methods.~~

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Table 1. Drought characteristics (number of droughts (n), mean duration (D **in days**) and mean deficit volume (V **or** H in mm)) of hydrometeorological variables precipitation (P), soil moisture storage (SM), groundwater storage (GW) and discharge (Q), calculated using four different drought identification techniques (Sect. 3).

		M_MA			D_MA			30D			D_FF		
catchment	variable	n	D	V / H	n	D	V / H	n	D	V / H	n	D	V / H
Narsjø	P	88	35.91	13.59	87	36.77	14.45	85	36.39	14.09	85	36.89	14.71
	SM*	54	63.43	7.45	57	62.72	7.58	52	61.9	7.51	61	58.18	7.05
	GW*	47	68.96	7.21	45	84.62	8.12	40	76.25	7.61	45	81.82	7.89
	Q	60	58.87	11.74	65	59.42	12.78	49	61.37	10.48	59	51.29	12.1
Upper-Metuje	P	45	35.27	14.06	44	37.43	15.56	42	36.5	14.68	47	38.81	16.96
	SM*	31	48.81	15.15	32	53.56	15.69	30	51.9	15.34	38	48.13	16.65
	GW*	16	113.88	11.24	15	139.87	12.66	14	131.29	12.64	18	106.28	11.43
	Q	27	66.04	3.22	30	63.53	3.81	26	66.65	3.55	29	90.45	6.36
Upper-Sázava	P	72	32.88	12.55	73	34.32	13.16	65	33.8	13.03	80	42.98	18.02
	SM*	49	51.12	18.24	52	52.23	18.55	48	52.21	18.04	58	50.91	19.22
	GW*	19	141.21	8.14	19	148	8.38	20	136.55	7.68	22	127.45	7.56
	Q	42	68.93	3.56	42	72.6	4.41	40	70.55	3.68	53	86.51	5.33
Nedožery	P	54	35.8	16.49	56	35.55	16.91	54	35.69	16.36	61	34.44	15.99
	SM*	45	47.13	22.87	48	49.94	22.6	45	49.18	22.09	53	46.42	21.73
	GW*	37	61	5.26	41	61.24	5.22	38	60.16	5.24	40	61.23	5.33
	Q	43	53.79	4.58	43	56.09	5.52	43	52.56	4.84	44	55.27	5.44
Upper-Guadiana	P	84	41.79	11	85	44.78	13.07	82	40.3	10.7	89	41.72	12.96
	SM*	47	80.7	22.12	51	83.96	22.46	44	84.5	23.52	52	81.88	22.17
	GW*	9	756.44	5.92	11	614.36	5.05	11	620.09	5.34	11	614.09	5.09
	Q	39	160.31	2.24	43	153.58	2.29	41	147.8	2.15	44	148.64	2.24

* is mean maximum deviation (H) used instead of mean deficit.

Table 2. ~~SD~~**Standard deviation** of drought characteristics (number of droughts (n), mean duration (D **in days**) and mean deficit volume (V **or** H **in mm**)) of hydrometeorological variables precipitation (P), soil moisture storage (SM), groundwater storage (GW) and discharge (Q), among the four threshold level approaches (Sect. 3).

catchment	variable	n	D	V / H
Narsjø	P	1.5	0.4	0.5
	SM*	3.9	2.3	0.2
	GW*	3.0	6.9	0.4
	Q	6.7	4.4	1.0
Upper-Metuje	P	2.1	1.5	1.3
	SM*	3.6	2.6	0.7
	GW*	1.7	12.2	0.8
	Q	1.8	12.6	1.4
Upper-Sázava	P	6.1	4.7	2.6
	SM*	4.5	0.7	0.5
	GW*	1.4	8.6	0.4
	Q	5.9	8.0	0.8
Nedožery	P	3.3	0.6	0.4
	SM*	3.8	1.7	0.5
	GW*	1.8	0.5	0.0
	Q	0.5	1.6	0.5
Upper-Guadiana	P	2.9	1.9	1.3
	SM*	3.7	1.8	0.7
	GW*	1.0	70.2	0.4
	Q	2.2	5.7	0.1

* is mean maximum deviation (H) used instead of mean deficit.

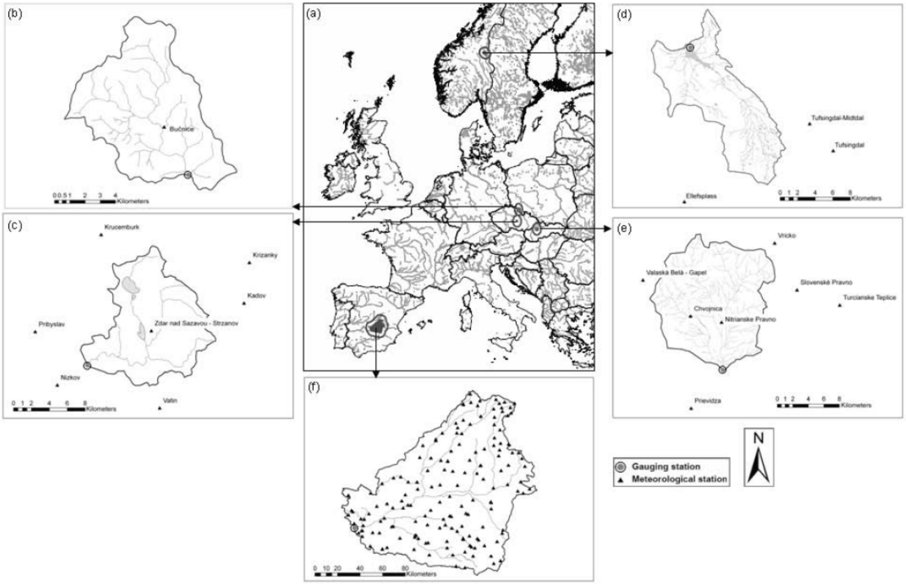

Fig. 1. (a) Location in Europe of the selected catchments, including gauging and meteorological stations; **(b)** Upper-Metuje catchment; **(c)** Upper-Sázava catchment; **(d)** Narsjø catchment; **(e)** Nedožery catchment; and **(f)** Upper-Guadiana catchment (reproduced from Van Loon and Van Lanen, 2012).

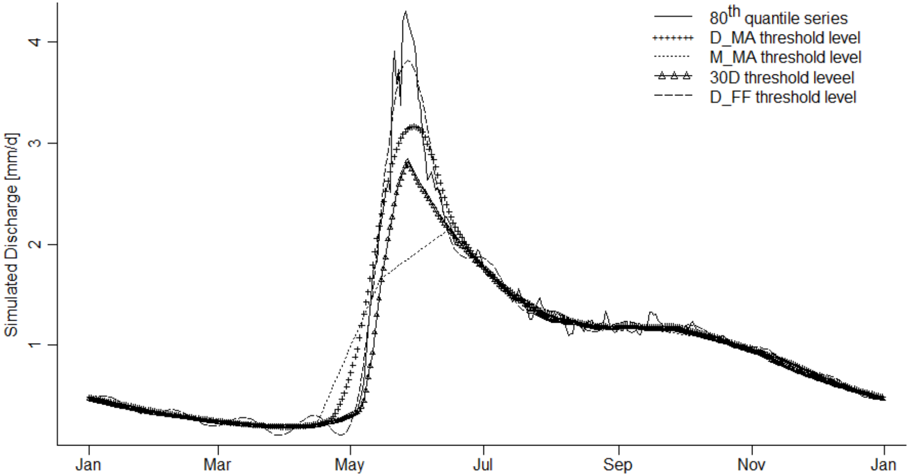

Fig. 2. Inter-comparison the annual curves of the four threshold levels and daily quantiles **for Narsjø catchment**.

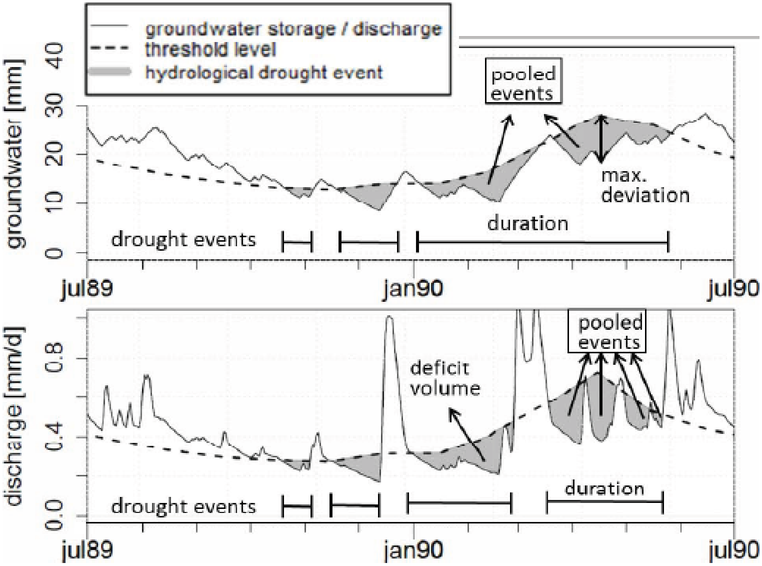

Fig. 3. Variable daily threshold level calculated from smoothing 80th percentile of monthly duration level by 30 days moving average (M_MA threshold level approach). We applied the pooling technique exclusively based on the duration of drought events. We used maximum deficit for state variables (groundwater storage, upper panel) and the cumulative sum of deficit volume for the flux variables (discharge, lower panel) as a measure of severity (reproduced from Van Loon and Van Lanen, 2012).

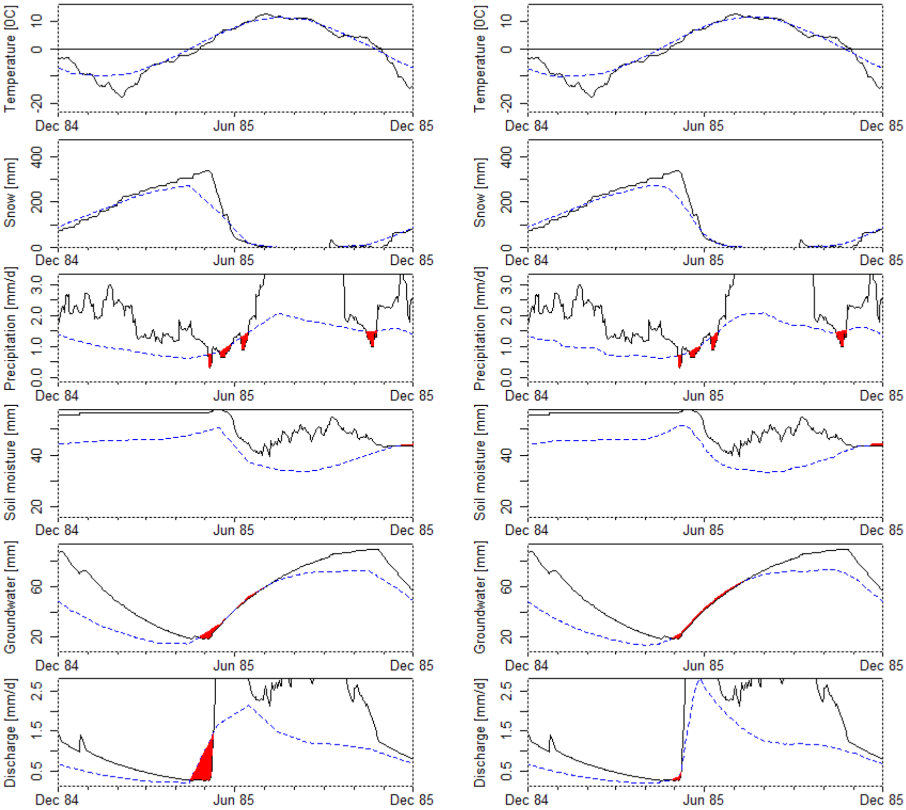

Fig. 4. Example of artefact drought event generated by M_MA threshold approach (left) as compared to 30D (right) for the Narsjø catchment.

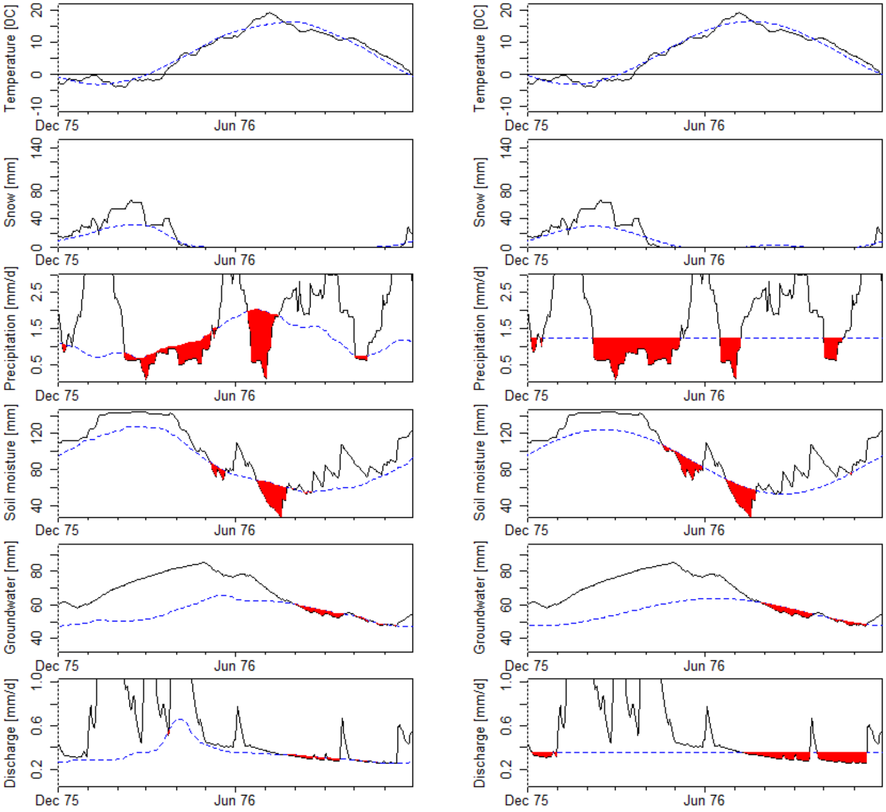

Fig. 5. Example of classical rainfall deficit drought type for Upper Sázava catchment during the period October 1975 to April 1977 as demonstrated using 30D (left) and D_FF (right) threshold level approaches.

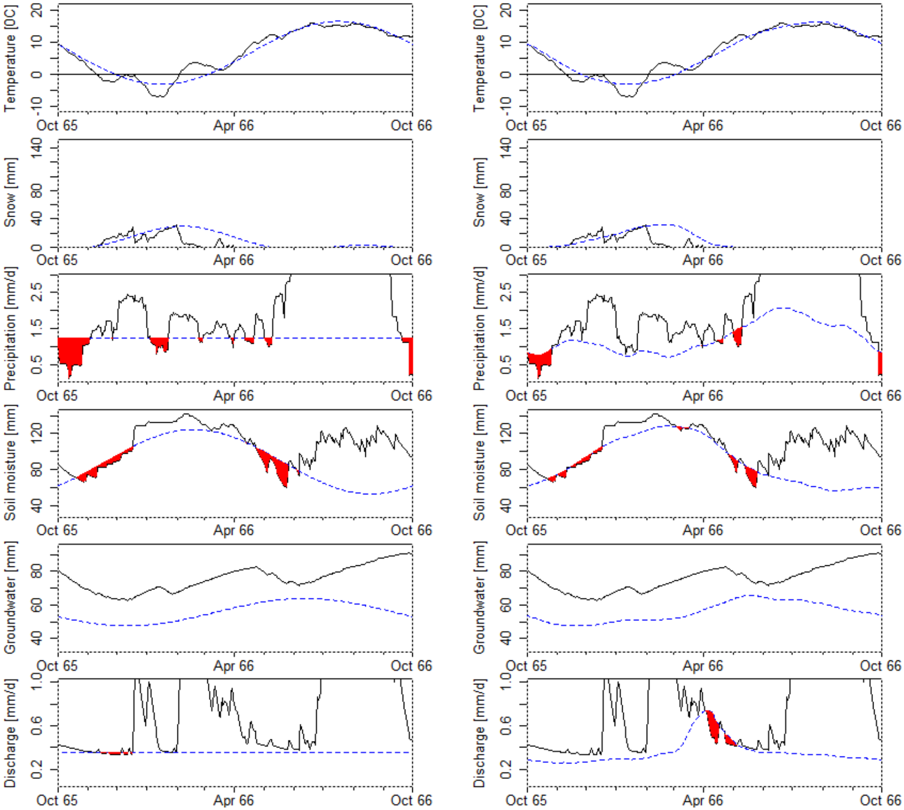

Fig. 6. Example of warm-snow season during the winter season from October 1965 to October 1966 in the Upper Sázava catchment as a result of D_FF threshold level calculation (left) and D_MA threshold level calculation (right).

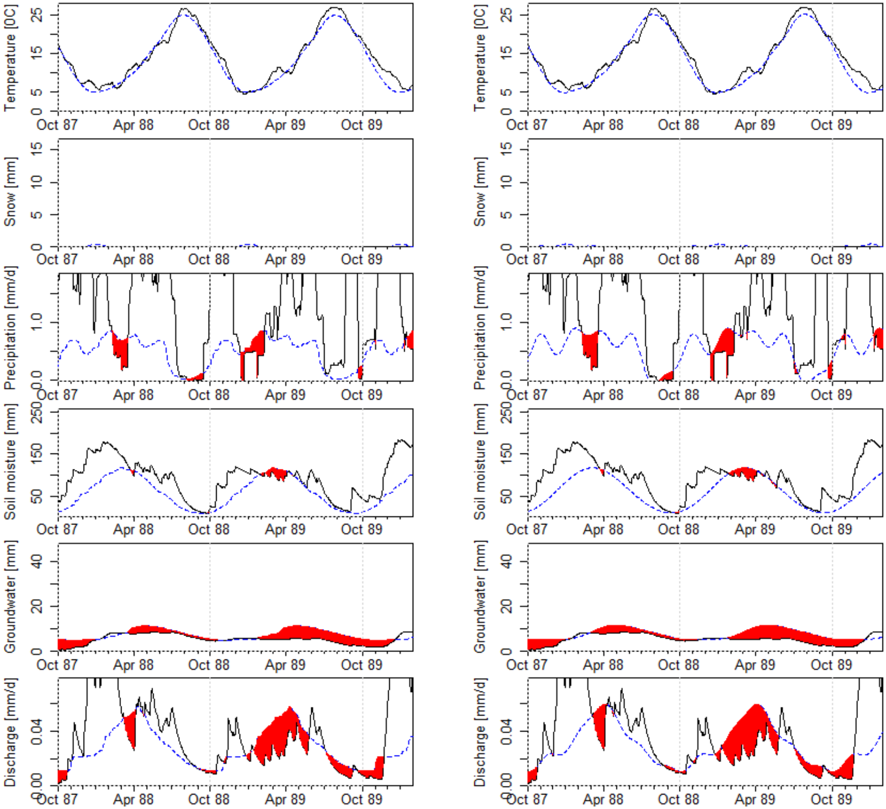

Fig. 7. Example of wet-to-dry-season drought in the Guadiana catchment during the period from January 1987 to January 1988 using two different threshold approaches: 30D (left) and D_FF (right).

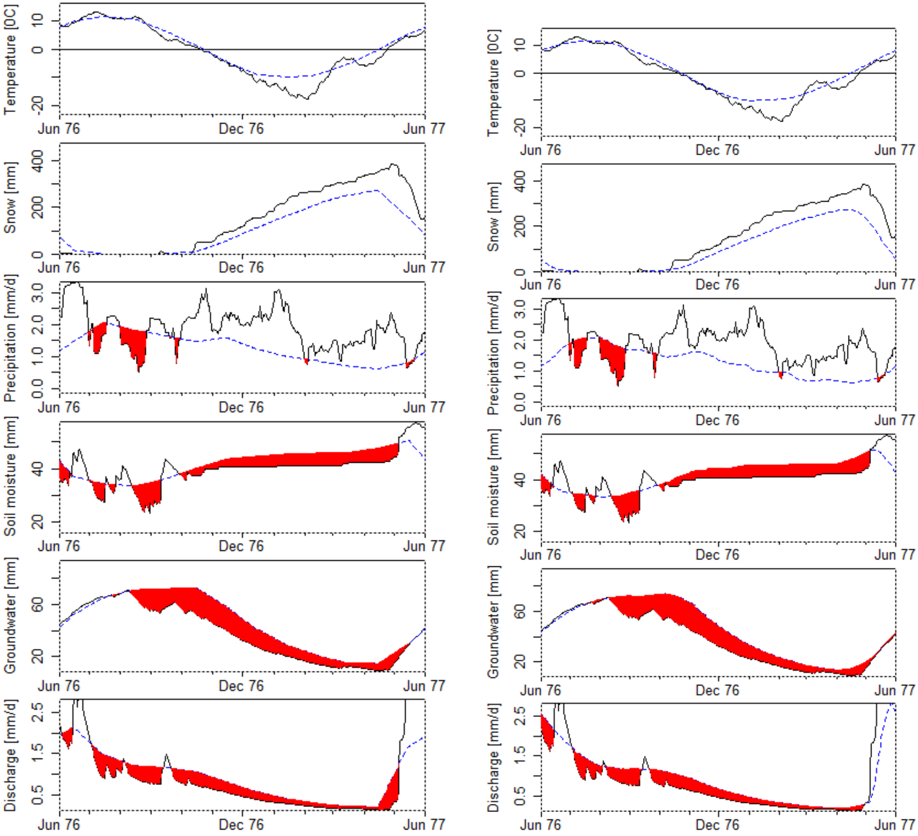

Fig. 8. Example of rainfall-to-snow-season drought in the Narsjø catchment during the period from June 1976 to June 1977 using two different threshold approaches: M_MA (left) and 30D (right).