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Drought indices suitable to study the linkages to large-scale climate drivers in regions with seasonal frost influence

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Abstract Based on a literature study the suitability of several common drought indices is evaluated for application in regional drought forecasting in climates with seasonal frost influence. In these regions hydrological droughts caused by a deficit in precipitation (summer droughts) and frost (winter droughts) have to be distinguished. Suitable drought indices should be objective, spatially and temporally robust, sensitive, interpretable and practical. They also need to enable drought forecasting, which is in this study considered to be based on a statistical model linking the drought indices to large-scale ocean and atmosphere patterns. None of the studied indices were found to be optimal for regional forecasting mainly due to a lack of robustness. It is suggested to use a set of three or four indices, including the Standardized Precipitation Index for meteorological drought, a streamflow drought index based on the threshold level method with a constant seasonal threshold, and a flow anomaly index to detect deviations from normal hydrological conditions.

Key words drought indices; hydrological drought; cold climate; regional forecasting; SPI; PDSI; PDHI; threshold level method; flow anomaly; streamflow

INTRODUCTION

Drought is a slowly developing natural hazard that can persist for a long time and extend over a large region. Water deficits during a drought can be large and in order to mitigate the impact of droughts long-range, forecasts are an important tool. Currently, drought forecasting exists mainly in warm and drier climates, and often in the form of monthly and seasonal precipitation and temperature forecasts based on relations to large-scale climate drivers like the El Niño–Southern Oscillation Index or sea surface temperatures, e.g. seasonal outlooks in Southern Africa (SADC-DMC, 2006) and Australia (Bureau of Meteorology, 2006). An exception is the US Seasonal Drought Outlook (NWS-CPC, 2006), that also considers other variables, e.g. soil moisture. Drought impacts can also be severe in temperate and cold regions and regions receiving water from cold mountainous regions such as large areas in the Mediterranean (Vicente-Serrano & López-Moreno, 2005). This study focuses on regions which experience prolonged frost periods of varying duration in the winter season.

Precipitation forecasts mainly address meteorological drought, which is defined as a deficit in precipitation. Temperature forecasts give an indication about snow accumulation and melting, and loss of water through evapotranspiration. A meteorological drought can develop into a soil moisture drought and a hydrological drought (deficit in surface water and groundwater; Wilhite & Glantz, 1985; Tallaksen & van Lanen, 2004). The different drought types affect different sectors of water usage, e.g. agriculture, water supply, hydropower and other industrial uses. The propagation of drought in the hydrological cycle depends on regional and local climatological and hydrogeological characteristics, and the different types of drought do not necessarily occur simultaneously or with the same severity. Separate forecasts for meteorological, soil moisture and hydrological droughts are therefore favourable. They should preferably be regional as severe droughts are often of large spatial extent. In regions with prolonged frost periods, soil moisture conditions are mainly of interest during the growing season. However, special considerations are needed in case of hydrological drought. When precipitation falls as snow it is temporarily stored on the surface. This implies that water levels in surface waters and groundwater can be low due to temperatures below zero (winter drought) and not because of a deficit in precipitation (summer drought). In regional studies hydrological droughts should be quantified so that consistent information for the whole range of climatological and hydrogeological characteristics in the region is provided. The quantification should also reflect local differences and be relative to "normal" hydrological conditions.

In drought monitoring, droughts are often described and quantified by indices, such as streamflow percentiles or the Palmer Hydrological Drought Severity Index (PHDI). Considering only one variable, streamflow percentiles are a single index, whereas the PHDI is a complex index, being based on several meteorological and hydrological variables. Not all drought indices are suitable for all regions and purposes. A general evaluation of some of the most common indices for different drought types is presented by Keyantash & Dracup (2002) and for streamflow drought by Fleig *et al.* (2006). In frost influenced regions a robust hydrological drought index needs to distinguish between summer and winter droughts, and should give consistent results for regions with and without frost influence. For streamflow drought important challenges are to allow a consistent quantification when a summer drought continues into a winter drought, which implies that the end of the summer drought is not clearly defined, and when the duration of the frost-free period varies between years or within the basin due to its large area or altitude range (Fleig *et al.*, 2006). Basins with glaciers have to be treated separately as they can experience above normal flows during a warm and dry summer period due to increased melt-water contribution.

In this study drought indices are evaluated for their suitability to study the linkages between hydrological drought and large-scale ocean and atmosphere patterns for regions with seasonal frost influence. The presence of such linkages could provide the basis for long-range monthly or seasonal drought forecasting with lead times of weeks or months. Considering the aforementioned challenges in frost influenced regions, the advantages and disadvantages of common hydrological drought indices are identified based on a literature study, and the applicability of each index is evaluated. The following requirements, which are mainly in accordance with general requirements listed by other authors (e.g. Keyantash & Dracup, 2002; Steinemann, 2003; Steinemann *et al.*, 2005, Fleig *et al.*, 2006), are considered to be important. Drought indices should be:

- objective, i.e. clearly defined, not requiring subjective choices of e.g. parameter values;
- spatially and temporally robust, i.e. statistically consistent and comparable for all climatological and hydrogeological conditions in the region;
- sensitive enough to show temporal development and within-regional drought patterns;
- interpretable for different user groups;
- practical in terms of calculations and data requirement, implying that sufficient historical data for developing a forecasting model are available.

As consistent groundwater data seldom are available for large regions, groundwater drought is not included in this evaluation. In the following sections four single and two complex indices are presented and evaluated. Conclusions are drawn in the final section.

SINGLE INDICES

Threshold level method

The threshold level method (theory of runs; Yevjevich, 1967) applied to annual, monthly or daily streamflow series identifies droughts as periods during which streamflow is below a predefined threshold. Derived indices include e.g. drought severity, which is expressed in terms of the total deficit volume (total water deficit) during such a period, and drought duration. For short time steps, e.g. daily, subsequent deficit periods separated by short excess periods are recommended to be pooled into larger events (e.g. Fleig *et al.*, 2006). This can be done by introducing a moving average procedure or a duration/volume based criterion for the excess periods (inter event method). A pooling procedure based on the Sequent Peak Algorithm (Vogel & Stedinger, 1987) is less favourable as drought events following major events might not be recognized. The threshold can either be constant or varying over the year (Fig. 1), representing a specific demand or determined relative to the natural flow regime. In comparative studies, percentiles from the flow duration curve (FDC) are often used, which give more consistent regional results than percentages of the mean (Tallaksen *et al.*, 1997). The constant and varying thresholds both have advantages and limitations. The disadvantage of a varying threshold is that it may include periods which are commonly not considered as droughts, e.g. periods with flow lower than normal due to a delayed onset of the snow melt flood. On the other hand, a varying threshold identifies deficit periods independently of seasonal characteristics and is therefore better suited to study the linkage to atmospheric circulation (Stahl, 2001). A constant threshold should only be applied to a predefined summer or winter season as otherwise mixed summer and winter droughts might result (Fleig *et*

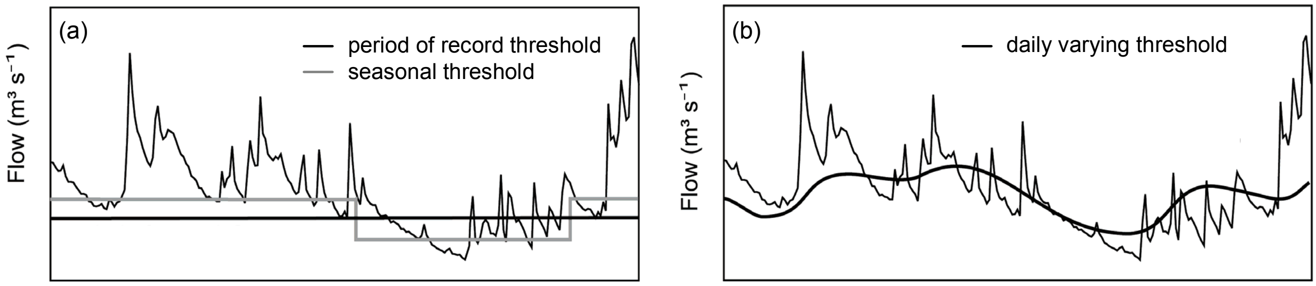

Fig. 1 Illustration of thresholds: (a) constant period of record and seasonal thresholds; (b) daily varying threshold (modified from Stahl, 2001).

al., 2006). Consequently, the threshold should be calculated based on data from this period only. However, FDCs for the summer season can vary considerably for summer seasons, differing only by a few weeks (Fleig, 2004) making a consistent regional threshold selection difficult. Furthermore, the threshold level method is often subjective in terms of choosing seasonal limits, threshold and pooling criteria. The major problem is that of mixed summer and winter droughts. This sets some limitations when using the otherwise well suited threshold level method in frost influenced regions.

Streamflow percentiles

Streamflow percentiles compare the average streamflow of the last n days to the FDC of n-day averages for that calendar day. Droughts can be classified in terms of daily exceedance frequencies determined from the n-day FDCs. The USGS (2006) classifies percentiles in the lower range (<10) as moderate, severe and extreme drought. They have, however, not yet defined duration and overall severity of a drought event, which could be done e.g. by introducing a threshold. Similar to the above-mentioned streamflow drought indices, streamflow percentiles are not capable of distinguishing between summer and winter droughts, but can be derived for a predefined season. This again delimits somewhat the applicability of streamflow percentiles in frost influenced regions.

Flow anomaly index

The flow anomaly index was introduced by Zaidman *et al.* (2002). For each day of the year the historical streamflow series for that day are transformed into a normal distribution by taking the natural logarithm. Subsequently, the daily flow anomaly index is calculated as the standardized departure from the mean daily flow for the considered day of the year. A basin is regarded to be under drought conditions when the index value equals or exceeds a threshold of 2.0, i.e. when the flow is at least two standard deviations lower than the mean flow for that day. An instantaneous deficit is defined as the difference between the flow anomaly and the threshold. These daily values can be summed up to a cumulative deficit over a period of days. Similar to the varying threshold approach, the flow anomaly index identifies atypical flows in both the low-flow and high-flow season, and droughts are defined independently of seasonal characteristics. The index has not yet been thoroughly tested, but the adopted standardization procedure is expected to make it spatially consistent (provided long enough data records) with the exception of the period during which both summer and winter droughts can occur. As the above-mentioned indices, the flow anomaly index is thus suited for frost influenced regions only when applied to a predefined season.

Standardized Precipitation Index

The Standardized Precipitation Index (SPI; McKee *et al.*, 1993) only considers precipitation and is thus a meteorological drought index defined for a single site. It can, however, be calculated for different averaging intervals ranging from one month to several years, and the intermediate and longer time scales can be considered to reflect the slower developing deficits in soil moisture, surface waters and groundwater. The SPI quantifies the current drought situation in terms of its occurrence probability, which is determined by fitting a probability distribution (usually a Gamma distribution) to at least 30 years of monthly data and transforming it into a standard normal distribution. It is therefore considered spatially consistent (Guttman, 1998). Droughts are indicated by negative SPI-values. Furthermore, the overall duration and magnitude (severity) of a drought event are defined, the latter as the negative sum of monthly SPI-values from the first month of a drought until its end (McKee *et al.*, 1993). A disadvantage is that the SPI might be misleading at short time scales (1–3 months) in regions with low seasonal precipitation. Understanding the climatology improves the interpretation of the SPI in these regions (Hayes *et al.*, 1999). Its spatial and temporal comparability with respect to the identification of hydrological drought is, however, limited since precipitation–runoff processes are variable in space and time. As such the SPI time-scale highest correlated with streamflow varies between basins (Szalai *et al.*, 2000) and seasons (Vicente-Serrano & López-Moreno, 2005). It is concluded that the SPI is well suited for meteorological drought forecasting, in particular as it is spatially robust, capable of quantifying the current deficit as well the deficit of the total drought event, and requires precipitation data only. For regions with a short growing season, a shorter time resolution, e.g. a biweekly SPI or a moving 30-day SPI calculated weekly, could be tested. However, no regionally comparable streamflow drought studies can be based solely on the SPI due to differences in runoff response.

COMPLEX INDICES

Palmer Drought Severity Index and Palmer Hydrological Drought Severity Index

The Palmer Drought Severity Index (PDSI) and the Palmer Hydrological Drought Severity Index (PHDI) were developed by Palmer in the mid 1960s (Heim, 2002) to quantify droughts for relatively homogenous regions. They are based on a water balance model considering two soil layers and the Thornthwaite method to estimate potential evapotranspiration. The two indices differ mainly in defining the end of a drought. The PDSI considers a drought to end as soon as an uninterrupted rise in moisture conditions begins, whereas the PDHI waits until the moisture deficit has vanished. The PDSI is therefore often regarded as a meteorological drought index and the PDHI as a hydrological drought index. Several drawbacks of the Palmer indices have been identified (e.g. Alley, 1984). Among these are: (a) the indices have been developed for semiarid and subhumid climates and are based on several arbitrary assumptions and values for variables and constants; (b) the natural lag between precipitation and runoff response is not considered for the PDSI; (c) snowfall, snow cover and frozen ground are not included; and (d) seasonal and annual changes in vegetation cover and root development are not considered. Consequently, the indices are not fully spatially and temporally comparable and the frequency with which drought events are classified into different severity classes varies between locations for the PDSI (and possibly the PHDI; Heim, 2002). The latter has been addressed by Wells *et al.* (2004), who developed a self-calibrating PDSI to enhance spatial comparability. However, as commented upon by the authors, it is not as spatially comparable as an index using nonlinear methods (e.g. the SPI). In particular the lacks of spatial robustness and consideration of snow make the Palmer drought indices less suited for regional studies in frost influenced regions.

Surface Water Supply Index

The Surface Water Supply Index (SWSI) was developed by Shafer & Dezman (1982) for regions where snow is an important component of the hydrological system. It is a monthly index representing the sum of weighted surface water supplies of a basin, including precipitation, snowpack, streamflow and reservoir storage. It thus accounts for snow storage and delayed runoff. Each component is expressed in a normalized way through its non-exceedance probability determined from a historical record. As the SWSI monitors the total surface water supplies, including snowpack, there is no need to distinguish between summer and winter droughts. However, a clear definition of "surface water supplies" is missing, and the weights are determined in different ways and often subjectively (Garen, 1993). According to Heddinghaus & Sabol (1991) the weights have to be redefined after changes in the basin and it is thus difficult to obtain a homogeneous time series of the SWSI. Furthermore, SWSI values are not comparable between basins, as the non-exceedance probabilities of the four components are summed up, resulting in a non-uniform distribution. It would be preferable to derive a single joint non-exceedance probability from a description of the components by a multivariate probability distribution (Garen, 1993). In its current form, the SWSI is not suitable for regional studies due to its lack of objectivity and robustness.

CONCLUSIONS

In this literature study several drought indices are evaluated for their suitability for regional forecasting of hydrological drought in areas with seasonal frost influence. In these regions two types of streamflow drought caused by different processes can occur, summer and winter droughts. Robust drought indices should be able to distinguish between these two types. However, none of the studied single drought indices are adequately capable of this distinction. A consistent identification of the drought governing processes based on temperature or precipitation data is also complicated as rivers respond differently. The complex drought indices are similarly not suited for regional studies due to a general lack of spatial robustness. Hence, no index is optimally suited for regional hydrological drought forecasting in seasonally frost influenced regions. One solution is to study summer and winter droughts separately by choosing a predefined season. Alternatively, an annual time resolution can be used. However, the obtained information is limited in these cases. It is therefore recommended to consider a set of drought indices addressing:

– meteorological drought based on the SPI of short and medium time scales, i.e. 1, 3 and 6 months;
– streamflow droughts occurring in a predefined season using a constant threshold;
– streamflow deviations, e.g. based on the flow anomaly index.

In addition, improvements in the presented indices could be tested, e.g. a biweekly SPI or the use of a multivariate probability distribution for the SWSI. The fact that streams with different regimes and characteristics, e.g. length of summer season or glaciers, respond differently to climatic conditions should be addressed by defining homogeneous sub-regions/samples with respect to drought behaviour. Still, it is important to study the linkages between drought and large-scale climate drivers at the scale of drought events, which might extend past the boundary of homogenous sub-regions. This requires that the spatial aspects of the drought are considered. For single indices derived at-site this can be done using various interpolation methods or by defining regional drought characteristics based on spatial information on the input variable at the grid or sub-basin scale. In the latter case the area aspect of the drought is included in its definition, which can be based on both single and complex indices. This will be the topic of a further study, where the above recommended indices will be included, addressing drought forecasting in a northern-European region.

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