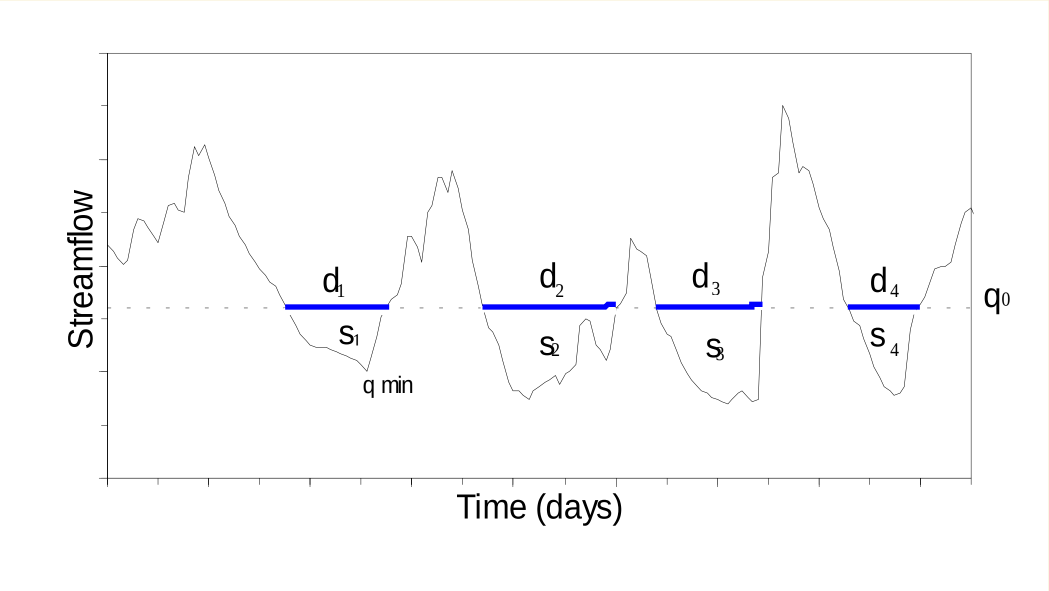
ARIDE

Assessment of the Regional
Impact of Droughts in Europe

Technical Report No. 6

Drought Event Definition



H. Hisdal and L. M. Tallaksen (Editors)

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Technical Report to the ARIDE project No.6:

Supplement to Work Package 2 Hydro-meteorological Drought
Activity 2.1 Event Definition

Contents

1. Introduction

H. Hisdal and L. M. Tallaksen

Extreme rainfall deficits and the resulting periods of low flow can have severe effects on water management issues. This includes river pollution and ecological aspects, reservoir design and management, irrigation, small power plants, drinking water supply, etc. Future increase in the demand for water will be most critical in periods of severe and extensive droughts. Incorrect estimations of low flow and drought might have serious consequences for ecology and economy.

Almost every climatic zone might experience drought although the characteristics can vary significantly between regions. Drought is, unlike aridity, a temporary phenomenon and can be characterised as a deviation from normal conditions.

Drought studies have been suffering from the lack of consistent methods for drought analysis. The first step in a drought analysis would be to define the drought event. Scientists have only agreed on very general definitions of a drought, e.g. Beran & Rodier (1985): "*The chief characteristic of a drought is a decrease of water availability in a particular period over a particular area*". Yevjevich (1967) claims that the lack of general acceptance of a precise and objective definition of drought, has been one of the principle obstacles to the investigation of drought. It is important to be aware that different definitions might lead to different conclusions regarding the drought phenomenon. For instance, it is possible that rainfall statistics summarised over a calendar year indicate no drought, whereas the moisture supply in the growing season does.

It is important, however, to stress that because drought affects so many sectors in society, there is a need for different definitions (Wilhite & Glantz, 1985). The particular problem under study, the data availability and the climatic and regional characteristics are among the factors influencing the choice of event definition. Wilhite & Glantz (1985) found more than 150 published definitions of drought, which might be classified in a number of ways. Some of the most common drought definitions are summarised in Tate & Gustard (2000), Demuth & Bakenhus (1994) and Dracup *et al.* (1980).

The terms "drought *event* definition" and "drought index" are frequently being confused. A drought index is often a single number characterising the general drought behaviour at a measurement site, whereas a drought event definition is applied to select drought events in a time series including the beginning and end of the droughts.

In this report different classification systems are summarised. A separate chapter discusses at-site drought definitions. These include definitions applicable to quantify temporal and spatial variations in meteorological droughts in terms of lack of precipitation, as well as hydrological droughts in terms of streamflow and groundwater deficits. A separate section addresses water resources management aspects. Droughts are regional in nature and regional drought event definitions are discussed separately. The report is a contribution to the European Commission supported project "Assessment of the Regional Impact of Droughts in Europe" (ARIDE). The event definitions chosen within specific activities of the ARIDE project are therefore described separately, including a discussion of their suitability in general. Emphasis has been paid to restrict the number of definitions applied within the project. If the event definition requires subjective choices to be made, recommendations are given. Some concluding remarks are given at the end.

2. Classifications

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Mawdsley et al. (1994) defined two classes or types of indicators:

- Environmental indicators are those hydro-meteorological and hydrological indicators, which measure the direct effect on the hydrological cycle. The nature of the water deficit might be related to precipitation, streamflow or soil moisture. These indicators can help identifying the duration and/or severity of a drought and can be used to analyse the drought frequency. Environmental definitions usually determine the degree of departure from average conditions.
- Water resource indicators measure severity in terms of the impact of the drought on the use of water in its broadest sense, for example, impact on water supply for domestic or agricultural use, impact on groundwater recharge, abstractions and surface levels, impact on fisheries or impact on recreation. This implies that an element of human interference as an increased water demand or mismanagement of water supply, as well as a lack of rainfall or runoff determines the drought. Hence, there is shortage of water to meet water supply needs.

Wilhite & Glantz (1985) categorise drought definitions into *conceptual* (definitions formulated in general terms) not applicable to current (i.e., real time) drought assessments, and *operational*. The latter category includes definitions attempting to identify the onset, severity and termination of drought episodes. In some publications (e.g. Tate & Gustard, 2000) the term operational drought is applied equivalent to water resource indicators, hence not consistent with the broad definition of Wilhite & Glantz (1985).

Another classification, based on a disciplinary perspective can be found in Dracup *et al.* (1980), where droughts are related to precipitation (meteorological), streamflow (hydrological), soil moisture (agricultural) or any combination of the three. A similar classification can be found in Wilhite & Glantz (1985), where four categories are identified:

- Meteorological drought: Usually expressions of precipitation's departure from normal over some period of time. Reflects one of the primary causes of a drought.
- Hydrological drought: Usually expressions of deficiencies in surface and subsurface water supplies. Reflects effects and impacts of droughts.
- Agricultural drought: Usually expressed in terms of needed soil moisture of a particular crop at a particular time.
- Socio-economic drought: Definitions associating droughts with supply of and demand for an economic good.

The three first groups could be defined as environmental indicators, the last group as a water resource indicator.

The relationship between the different drought categories can be illustrated as in figure 1. A meteorological drought in terms of lack of precipitation is the primary cause of a drought. It usually first leads to an agricultural drought due to lack of soil water. If precipitation deficiencies continue a hydrological drought in terms of surface water deficits develops. The groundwater is usually the last to be affected, but also the last to return to normal water levels.

A similar, “disciplinary” classification based on McMahon & Diaz Arenas (1982) is used by Tate & Gustard (2000) to categorise droughts into climatological, agro-meteorological, river flow and groundwater droughts.

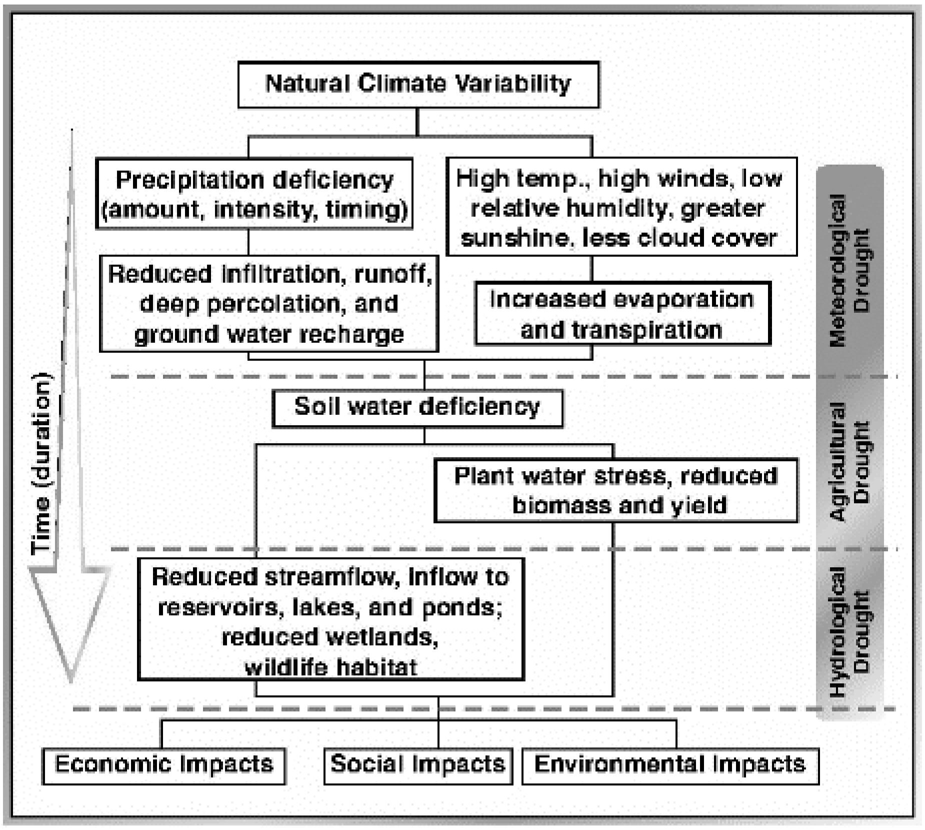

Fig. 1 The sequence of drought impacts associated with meteorological, agricultural and hydrological drought (Source: National Drought Mitigation Centre, http://enso.unl.edu/ndmc/enigma/def2.htm)

A different approach is to subdivide the environmental group based on whether the drought event is based on one or several variables. A single variable or simple index would typically be rainfall or streamflow deficits. Multivariable or complex indices include many elements of the hydrological cycle, e.g. a combination of meteorological factors as precipitation and evapotranspiration. A quite comprehensive list of complex and simple aridity and drought indices as well as statistical measures applied as drought indices can be found in WMO (1975).

Several complex drought indices have been developed, of which one of the most frequently applied is the Palmer Drought Severity Index, PDSI (Palmer, 1965). Although the PDSI is sometimes used as an indicator of hydrological drought, it is more correctly referred to as a meteorological drought indicator, applying the disciplinary perspective of

Dracup *et al.* (1980). Other multivariable indices are e.g. the Surface Water Supply Index, SWSI (Shafer & Dezman, 1982), the Standardised Precipitation Index, SPI (McKee *et al.*, 1993) and the Crop Moisture Index, CMI (Palmer, 1968). In an American study (Soulé, 1992) the regional patterns of different drought indices based on the Palmer model (Palmer, 1965) are compared (the PDSI itself, a monthly moisture anomaly index, ZINX, and a hydrologic drought index, PDHI). The results indicate that the choice of drought index has a major impact on the spatial patterns observed. Patterns of drought frequency identified using the fast responding ZINX are largely inverse of those identified using the PDSI and PHDI. Varying the parameters, e.g. intensity (the magnitude of the index) and minimum duration (number of consecutive months with a certain intensity) in a drought event definition had only minor influence on the spatial patterns. Hayes (1999) gives a description of many multivariable indices, and refers to several studies where the indices are applied.

As droughts are regional in nature and commonly cover large areas and extend for long time periods, it is important to study such events within a regional context. The properties of regional droughts can be studied by studying the spatial pattern of at-site (point) droughts (e.g. Tallaksen & Hisdal, 1997; Hisdal *et al.*, 2001). Another approach is to study regional variables like the area covered by drought and total deficit over the drought area (Tase, 1976; Sen 1980; Santos, 1983; Rossi *et al*., 1992; Sen, 1998; Vogt & Somma, 2000). Regional drought analyses are often based on at-site event definitions where the areal aspect is included by studying the spatial pattern of point values and without introducing a separate, regional drought event definition. Different approaches to regional drought analyses have been reviewed by Rossi *et al*. (1992), applying precipitation as an example. The next two chapters describe at-site and regional drought definitions respectively. Complex drought indices as the PDSI and the SWSI are calculated for catchments or regions. Still, they are described under "at-site" drought definitions, as they do not include the area covered by drought as a dynamic variable (varying in time).

3. At-site drought definitions

3.1 Meteorological drought

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The question of time resolution, whether to apply annual, monthly or daily data, will depend on the climatological regime under study and the specific problem to be solved. In the temperate zone a given year might include both severe droughts (seasonal droughts) and months with abundant precipitation implying that annual data would often not reveal severe droughts. Other regions like the Mediterranean are more likely to experience droughts lasting for several years, multi-year droughts, which supports the use of a monthly or an annual time step.

The characterisations of meteorological drought given below are based on Krasovskaia & Gottschalk (1995) and Wilhite & Glantz (1985).

3.1.1 General definition

A general definition based on precipitation amounts and duration is: "drought is a period of more than some particular number of days with precipitation less than some specified small amount" (Great Britain Meteorological Office, 1951). The chosen thresholds are generally site and/or region specific, as well as depending on the problem under study. Care must be taken when definitions like this are applied to characterise and compare droughts in different regions.

3.1.2 Deviations from normal conditions and deciles

Deviations from normal conditions could be rainfall "surplus" or "deficit" with respect to a percentage of normal rainfall (referred to as pluviosity by Beran & Rodier (1985)). Normal rainfall is assumed to be the mean rainfall for a certain period (month, season or year). Some scientists raise criticism against defining droughts as deviations from normal conditions, because the calculation of normal precipitation often is based on a period too short (e.g. thirty years) to represent long-term variations. Another drawback is the inability to describe adequately the relative severity of deficits between widely scattered locations (Beran & Rodier, 1985). This is because the variability of rainfall varies spatially meaning that for instance a 30 per cent shortfall will be experienced with different frequency in regions of different variability. An alternative to overcome this problem would be to apply measures of precipitation shortfall that allow for different variability at different locations. This could be done by the use of percentiles. Gibbs & Maher (1967) used the limits of each ten per cent of the cumulative frequency distribution of monthly and annual precipitation totals to classify wetness conditions in Australia.

A specific threshold (percentage, percentile etc.), based on the problem under study has to be defined in order to extract the drought events. The method could therefore be referred to as a threshold level method (figure 2). This allows for a characterisation of the droughts in terms of a number of variables as described and illustrated in sections 3.2 and 5.1.2.

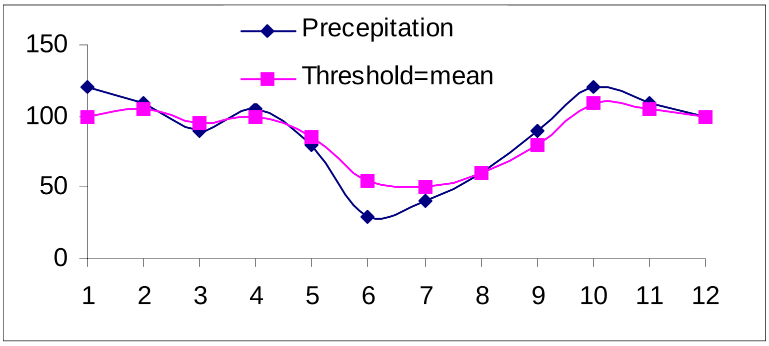

Fig. 2 **Monthly precipitation and mean monthly precipitation. A drought occurs when the monthly precipitation is below the mean monthly precipitation**

3.1.3 Effective precipitation

Effective precipitation is defined as rainfall sufficient to counteract evapotranspiration and to maintain soil moisture above the wilting point. A rainless period is defined to last as long as precipitation is below the effective precipitation (illustrated in figure 3) and its severity is given by the total amount of precipitation during this period or as the difference between effective and observed precipitation. This definition is closely related to the descriptions given in both sections 3.1.1 and 3.1.2.

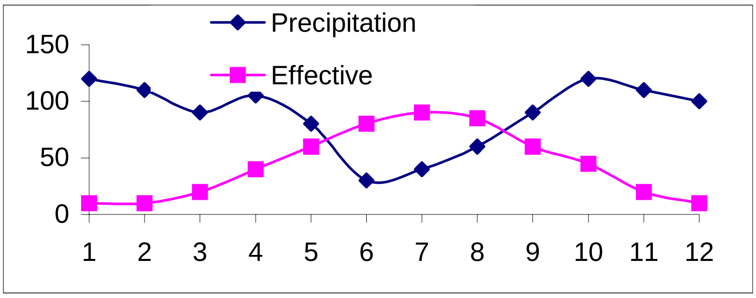

Fig. 3 **Mean monthly precipitation and mean monthly effective precipitation**

3.1.4 A multivariable index, the PDSI

The first comprehensive drought index developed in the United States and the most frequently applied meteorological multivariable drought index is the Palmer Drought Severity Index (PDSI). A brief description based on Hayes (1999) is here given. The index measures the departure of the moisture supply from normal conditions. Moisture supply is calculated from the water balance of a two-layer soil model using monthly mean precipitation and temperature data as well as the local available water content of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Human impacts on the water balance, such as irrigation, are not considered. Complete descriptions of the equations can be found in the original study by Palmer (1965). The Palmer Index varies roughly between -6.0 (dry) and +6.0 (wet). Palmer arbitrarily selected the classification scale of moisture conditions based on his original study areas in central Iowa and western Kansas (Palmer, 1965). The Palmer Index is designed so that a -4.0 in South Carolina has the same meaning in terms of the moisture departure from a climatological normal as a -4.0 in Idaho (Alley, 1984).

The index provides a measure of the abnormality of recent weather for a location, and places the current condition in a historical context. It also allows spatial and temporal representations of historical droughts. There are, however, considerable limitations as pointed out by Alley (1984), of which some of the most important are:

- The quantification of the intensity as well as the beginning and end of a drought has little scientific meaning and is subjectively selected based on a study of Iowa and Kansas.
- The delay between the timing of precipitation and the resulting response of river flow and groundwater levels is not considered and may lag emerging drought by several months.
- The suitability for mountainous areas and areas with frequent climatic extremes is less favourable.
- The sensitivity to the actual water content of a soil type is large.
- The potential evapotranspiration is only approximated, applying the Thornthwaite method.
- The PDSI is not designed for large topographic variations across a region and it does not account for snow accumulation and snowmelt.

3.2 Hydrological drought – streamflow

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In Beran & Rodier (1985) a distinction is made between streamflow droughts and low flows. The main feature of a drought is said to be the deficit of water for some specific purpose. Low flows are normally experienced during a drought, but they feature only one element of the drought, i.e. the drought magnitude. Low flow studies are described as being analyses aimed at understanding the physical development of flows at a point along a river at a short-term (e.g. daily time resolution). Hydrological drought analyses in terms of streamflow deficits are said to be studies over a season or longer time periods and in a regional context. However, also short-term (less than a season) streamflow deficits might be defined as droughts and treated at a fixed point in space (e.g. Zelenhasic & Salvai, 1987).

As discussed in the introduction, drought indices (i.e. low flow indices in case of streamflow), and drought event definitions are often seen as the same. However, they are not, even if both describe the same part of the hydrograph. A streamflow drought event definition quantitatively defines whether the flow can be regarded as being in a drought situation or not and gives the duration of a drought, whereas low flow indices characterise specific features of the low flow range. The most frequently applied low flow index is the minimum annual *n*-day average discharge. In the United States and in the United Kingdom, a seven days averaging period is often considered (TCLFE, 1980;

Gustard *et. al.*, 1992). In the following a detailed description of the threshold level method defining drought events is given.

3.2.1 The threshold level method

The most frequently applied quantitative definition of a drought is based on defining a threshold, q_0, below which the river flow is considered as a drought (also referred to as a low flow spell in the literature). The threshold level method generally study runs below or above a given threshold and was originally named method of crossing theory (Tallaksen, 2000). The method is relevant for storage/yield analysis and is associated with hydrological design and operation of reservoir storage systems. Important areas of application are hydropower and water management, water supply systems and irrigation schemes.

The method was first developed by Rice (1945) and later extended and summarised by Crámer & Leadbetter (1967). Early application of crossing theory in hydrology includes Yevjevich (1967), where the method is based on the statistical theory of runs for analysing a sequential time series. Statistical properties of the distribution of water deficits, run-length (drought duration, d_i), run-sum (deficit volume or severity, s_i) are recommended as parameters for at-site drought definition. Simultaneously it is possible to define the minimum flow, q_{min} and time of occurrence (figure 4). The minimum flow can be regarded as a low flow measure, one of several characteristics of a streamflow drought event. The time of drought occurrence has been given different definitions as for instance the starting date of the drought, the mean of the onset and the termination date or the date of the minimum flow. Often another drought index, the drought intensity, is defined as the ratio between drought deficit volume and drought duration.

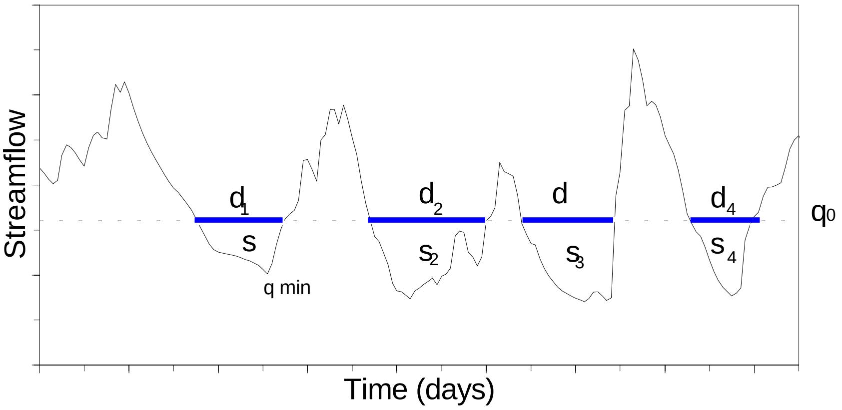


Fig. 4 Definition of low flow and drought characteristics (modified from Tallaksen, 2000)

<u>Threshold selection</u>

The threshold might be chosen in a number of ways and the choice is amongst other a function of the type of water deficit to be studied (Dracup *et al.*, 1980). In some applications the threshold is a well-defined flow quantity, e.g. a reservoir specific yield. It is also possible to apply low flow indices, e.g. a percentage of the mean flow or a percentile from the flow duration curve. A flow duration curve represents the relationship between the magnitude and frequency of daily, monthly or some other time interval of streamflow. It can be calculated in various ways (Vogel & Fennessey, 1994). If daily data are analysed, the flow duration curve shows the relationship between each daily flow (usually expressed as a percentage of the period-of-record mean flow) and the corresponding flow exceedance. Flow exceedance is a dimensionless index that expresses the proportion of time that a specified daily flow is equalled or exceeded during the period of record (Gustard *et al.*, 1992). Expressing flows as exceedance values allows flow conditions in different rivers to be compared. The flow exceedance is often given in terms of percentiles. For instance the 90th percentile flow, or Q90, is the flow which is equalled or exceeded for 90% of the period of record. Flow duration curves for two contrasting types of British catchments are shown in figure 5. Curve A is typical of a lowland chalk stream. The low variability of flows in this type of regime is reflected by a flat flow duration curve. Curve B is characteristic of an impermeable catchment, with a flashy flow regime and a high variance of daily flows.

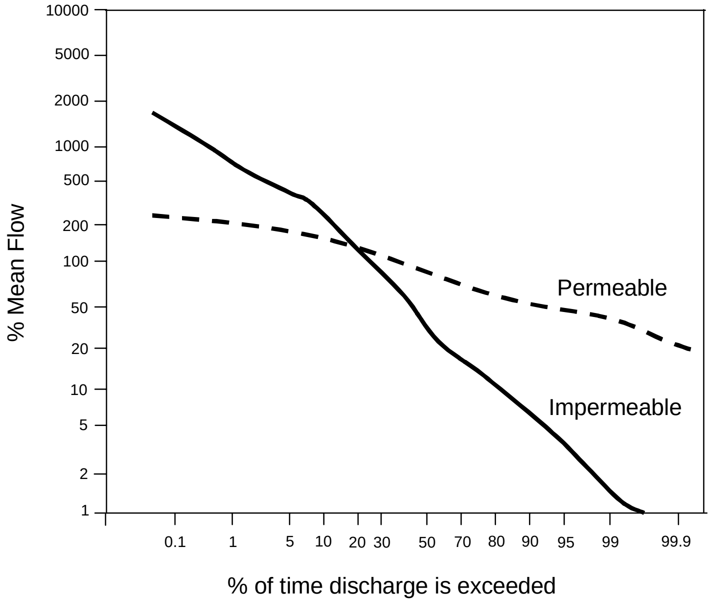


Fig. 5 Flow duration curves for contrasting flow regimes (modified from Gustard *et al.*, 1992) Curve A: Permeable, Curve B: Impermeable

In a regional study, the lack of long series over larger areas may impose restrictions to the use of very low threshold levels due to the presence of too many zero-drought years (the flow never falls below the chosen threshold in a year). On the other hand, the problem of droughts lasting longer than a year (multi-year droughts) becomes more severe for increasing threshold level and care should be taken when selecting a relatively high threshold level.

The threshold might be fixed, as applied in sections 5.1, 5.2 and 5.5, or vary over the year, as in sections 5.3 and 5.4. A threshold is regarded as fixed if a constant value is used for the whole series. If the threshold is derived from the flow duration curve it implies that the whole streamflow record (or a predefined period) is used in its derivation. This is illustrated in figure 6 a) applying a threshold for the period of record of Q90. If summer and winter droughts are studied separately (see next section), the threshold can also be fixed, but is then based only on flow data from the relevant season studied (figure 6 a). A variable threshold is a threshold that varies over the year, for instance using a monthly (figure 6 b) or daily (figure 6 c) varying threshold level.

The variable threshold approach is adapted to detect streamflow deviations during both high and low flow seasons. Unusual low flows during high flow seasons might be important for later drought development. However, periods with relatively low flow either during the high flow season or for instance due to a delayed onset of a snowmelt flood, are commonly not considered a drought. Therefore, the events defined with the varying threshold should be called streamflow deficiency or *streamflow anomaly* rather than streamflow drought.

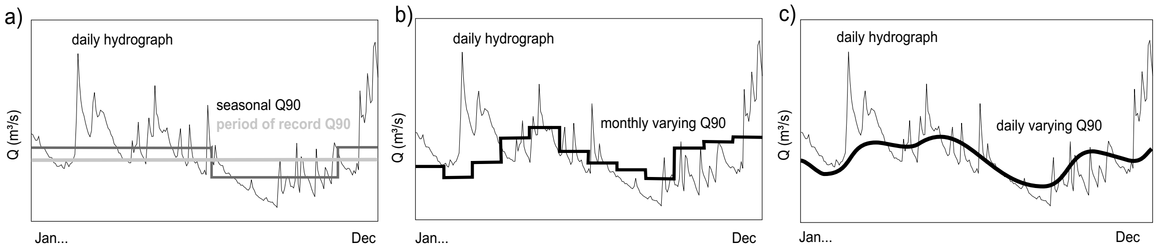


Fig. 6 Illustration of threshold levels; a) fixed threshold b) monthly varying threshold c) daily varying threshold

A variable threshold can thus be used to define periods of streamflow deficiencies as departures or anomalies from the 'normal' seasonal low flow range. A daily varying threshold level can for example be defined as an exceedance probability of daily flow duration curves. Exceedances derived on a daily basis may be misleading where the number of record years is small because the complete range of flows is not sampled. To increase the sampling range and smooth the threshold cycle the daily exceedance can be calculated from all flows that occur within an L-day window. For example applying a 31-day window, the flow exceedance on 1 June would be calculated from all discharges recorded between 17 May and 16 June in each year of the period of record.

Using a period of record of *n* years, and provided there are no gaps in the gauged daily flow record, the flow exceedance on any given day of the year is given by:

$$E_d = \frac{((\mathrm{L}n+1)-\mathrm{k}_\mathrm{d})\cdot 100\,\%}{\mathrm{L}n} \tag{1}$$

where E_d, is the flow exceedance on day d, L is the length of the window in days, n is the number of record years and k_d is the ranking position of the gauged daily flow on day d (flows are ranked in ascending order) in the set of Ln values.

A stepwise illustration of the flow duration curve calculation is seen in figure 7. Derivation of daily, monthly and seasonal period of record flow duration curves are illustrated in figure 7 a) and the exceedance percentiles for each day of the year are calculated from a L-day moving window as demonstrated in figure 7 b). One of the resulting daily exceedances (e.g. Q90) can be applied as a varying threshold (refer figure 6 c). A streamflow anomaly is said to occur when the streamflow of a given day is lower than the threshold for that particular day.

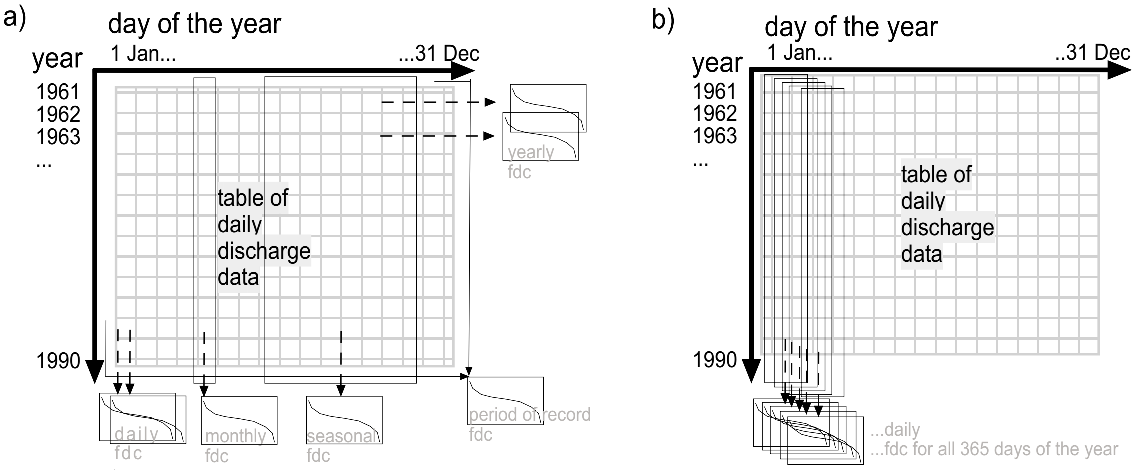


Fig. 7 Scheme for determination of different flow duration curves for the threshold level definitions; a) calendar units (day, month, season) b) moving window (daily)

Summer and winter droughts

Normally a drought is caused by lack of precipitation. However, snow and ice affected regions often experience their lowest flows during the winter months due to precipitation being stored as snow and streamflow reduced by freezing. There are also large transition regions where the lowest flow can be found either in winter or summer. It is necessary to separate between the two events of summer and winter droughts in order to make a consistent analysis of droughts (Tallaksen & Hisdal, 1997). A detailed description of how this can be done is given in Hisdal *et al*. (2001).

Annual Maximum Series (AMS) and Partial Duration Series (PDS)

The aim of a drought analysis is often to try to find a probability distribution of drought duration and deficit volume to be able to predict the risk of future droughts. The two most common extreme value analyses models are the annual maximum/minimum series (AMS) model and the partial duration series (PDS) model. An AMS consists of the largest/smallest event within each year, whereas a PDS contains all events below/above a threshold. The definition of the AMS is more straightforward providing the hydrometric year can be properly defined (Tallaksen *et al.*, 1997). In favour of the PDS model is the more consistent definition of the extreme value region, considering not only the largest annual events. In case of low threshold levels the occurrence of zero-drought years may significantly reduce the information content of the AMS. In the PDS, however, minor droughts may significantly distort the extreme value modelling, and a procedure for exclusion of minor droughts should be imposed. Whether to use an AMS or PDS model depends on the available data and the type of analysis to be carried out.

Time resolution and pooling procedures

The question of time resolution, whether to apply annual, monthly or daily streamflow series is similar as for precipitation, depending on the hydrological regime under study and the specific problem to be solved.

The drought event definition by Yevjevich (1967) was originally based on the statistical theory of runs for analysing sequential time series with a time resolution of one month or longer. The approach has also been used for analysing streamflow droughts from a daily-recorded hydrograph (Tallaksen *et al.*, 1997; Tallaksen & Hisdal, 1997; Kjeldsen & Lundorf, 1997; Zelenhasic & Salvai 1987). These studies demonstrated the potential of this method for a complete description of the stochastic process of seasonal (within year) droughts. However, the use of a daily time resolution introduces two special problems; dependency among droughts and the presence of minor droughts. During a prolonged dry period it is often observed that the flow exceeds the threshold level for a short period of time and thereby a large drought is divided into a number of minor droughts that are mutually dependent (figure 8). To avoid these problems that could distort an extreme value modelling, a consistent definition of drought events should include some kind of pooling in order to define an independent sequence of droughts (Tallaksen, 2000).

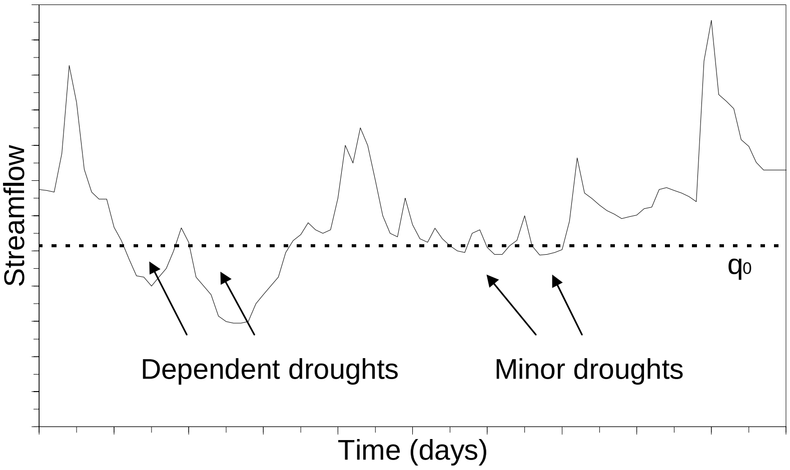


Fig. 8 Daily time series of flow illustrating the problem of mutual dependence and minor droughts (modified from Tallaksen, 2000)

Tallaksen *et al.* (1997) compared and described three different pooling procedures; the moving average procedure (MA), the sequent peak algorithm (SPA) and the inter-event time and volume criterion (IC). Their results indicate that the IC method is inferior to the MA and SPA methods and is therefore not explained further. MA simply smoothes the time series applying a moving average filter and it is recommended to apply a moving average interval of 10 days.

The most commonly used procedure for design of reservoirs based on annual streamflow data is the mass curve or its equivalent, the SPA (e.g. Vogel & Stedinger, 1987). Analogous, let q_t denote the *daily* inflow to a reservoir and q_0 the desired yield, then the storage w_t required at the beginning of the period t read (Tallaksen *et al.*, 1997):

$$w_t = \begin{cases} w_{t-1} + q_0 - q_t, & \text{if positive} \\ 0 \qquad , & \text{otherwise} \end{cases} \tag{2}$$

An uninterrupted sequence of positive w_t, $\{w_t,\ t=\tau_0,\ldots,\tau_e\}$, defines a period with storage depletion and a subsequent filling up (figure 9). The required storage in that period, $max\{w_t\}$, defines the drought deficit volume (s_i) and the time interval from the beginning of the depletion period, τ_0, to the time of the maximum depletion, τ_{max}, defines the drought duration ($\tau_{max}-\tau_0+1= d_i$). Based on this method two droughts are pooled if the reservoir has not totally recovered from the first drought when the second drought begins.

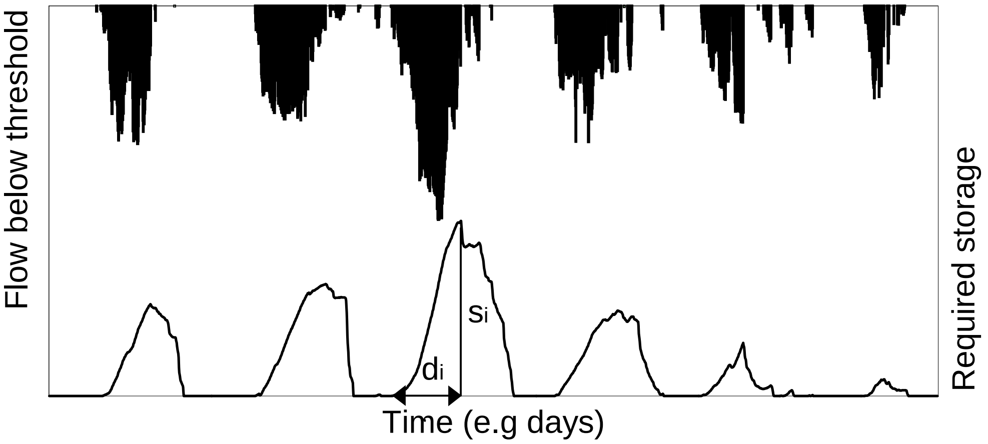


Fig. 9 Definition of drought events using the sequent peak algorithm (SPA) method (Tallaksen *et al.*, 1997)

The presence of multi-year droughts restricts the use of the SPA method for analysis of within year droughts, to very low threshold levels. Kjeldsen *et al.* (2000) showed that the SPA generally extracts larger extreme events than MA using a partial duration series approach. The advantage of the SPA method is that there is no parameter to be determined prior to the use of the method, as compared to the choice of averaging interval in the MA method. However, the number of minor droughts is larger in the SPA method. Kjeldsen *et al.* (2000) suggest removing 40% of the smallest droughts because these small events complicate the frequency distribution modelling of the most extreme events. The choice of 40% is arbitrary and the censoring percentage must be regarded as a parameter of the method. The main advantage of the MA pooling method is that it reduces the problem of minor droughts at the same time as mutually dependent droughts are pooled. The SPA method on the other hand has a more straightforward interpretation as the observed data are used directly. The threshold can be interpreted as the desired yield from a reservoir, and the drought deficit volume defines the required storage in a given period.

3.2.2 A multivariable index, the SWSI

There are several multivariable hydrological drought indices, including the complementary to the PDSI – the Soil Water Supply Index (SWSI) (Shafer & Dezman, 1982). The following description is based on Hayes (1999). The SWSI is designed to be an indicator of surface water conditions and Hayes described the index as "mountain water dependent," in which snowpack is a major component. The objective of the SWSI is to incorporate both hydrological and climatological features into a single index value resembling the Palmer Index for each major river basin in the state of Colorado. These values would be standardised to allow comparisons between basins. Four inputs are required for the SWSI calculation: snowpack, streamflow, precipitation, and reservoir storage. The SWSI is computed from only the snowpack, precipitation, and reservoir storage in the winter. During the summer months, streamflow replaces snowpack as a component within the SWSI equation. Each component has a monthly weight assigned to it depending on its typical contribution to the surface water within that basin, and these weighted components are summed to determine a SWSI value representing the entire basin. Like the Palmer Index, the SWSI is centred on zero and has a range between -4.2 (dry) and +4.2 (wet).

One of the advantages of the SWSI is that it gives a representative measurement of surface water supplies across a region. Several characteristics of the SWSI limit its application. Changes in the water management within a basin, such as flow diversions or new reservoirs, mean that the entire SWSI algorithm for that basin needs to be redeveloped to account for changes in the weight of each component. Thus, it is difficult to maintain a homogeneous time series of the index (Heddinghaus and Sabol, 1991). Extreme events also cause a problem if the events are beyond the historical time series, and the index will need to be re-evaluated to include these events.

3.3 Hydrological drought – groundwater

L. Peters and H. van Lanen

Although groundwater is an important source of water, it is largely ignored in many drought analyses. In an overview of drought event definitions from Wilhite & Glantz (1985) groundwater is mentioned only once as one of the parameters that should be monitored in case a drought warning has been issued. In an overview of drought definitions from a hydrological perspective (Tate & Gustard, 2000), one short section is about groundwater drought. In a comprehensive overview of the 1988-1992 drought in the UK (Marsh *et al.*, 1994), the effect of the drought on groundwater levels is discussed, but no definition of a groundwater drought is given.

In the literature groundwater drought event definitions are rare. A conceptual definition is given by Calow *et al.* (1999): "We use the term 'groundwater drought' to describe a situation where groundwater sources fail as a direct consequence of drought". This definition is used in a project about management for groundwater drought in Africa that mainly focuses on failure of wells and boreholes. A groundwater drought sensitivity map is compiled, using the concept of physical and human vulnerability. This definition of a groundwater drought apparently also incorporates human demand of water.

Van Lanen & Peters (2000) present an overview of definitions and effects of groundwater droughts. The following definition of a groundwater drought is given in the conclusion: "A groundwater drought occurs if in an aquifer the groundwater heads have fallen below a critical level over a certain period of time, which results in adverse effects." Like in Marsh *et al.* (1994), the focus is on groundwater levels. But a period of low groundwater levels is considered to be a drought only when adverse effects are noticeable. These effects do not solely apply to the aquifer itself, but also include the discharge from the aquifer to e.g. the riparian area, springs and brooks. Hence, socio-economic, ecological and environmental aspects are introduced. The critical level can be defined as some percentile of the groundwater hydrograph and is derived from a socio-economic or environmental point of view.

In some countries groundwater levels are monitored to detect emerging groundwater droughts (for example in the UK and The Netherlands). In this case groundwater droughts at a particular moment (e.g. a month) are assumed to occur if the groundwater level drops below a certain threshold. This threshold is time-dependent and is derived from a probability or frequency distribution based upon historical data for that particular period. In the Netherlands the term groundwater droughts as such is not used. Groundwater hydrographs are used to show groundwater droughts implicitly (e.g. van der Sluijs & de Gruyter, 1985). In the Netherlands the 95 percentile of the daily hydrograph is chosen as the threshold below which a critical groundwater level is reached (figure 10).

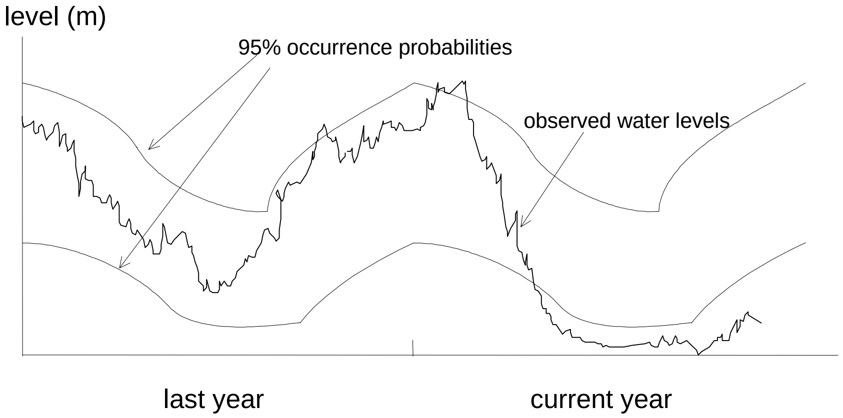


Fig. 10 Monitoring of groundwater droughts using observed groundwater data (van Lanen and Peters, 2000)

Warren (1994) does not provide a groundwater drought definition, but mentions that the winter recharge is the important aspect for groundwater droughts. In many climate types hardly any recharge prevails during the summer, because evapotranspiration exceeds rainfall. The concept of winter groundwater drought is introduced, meaning a winter with low recharge.

3.3.1 Groundwater drought parameters

The type of variables on which a drought definition is based determines the type of drought that is investigated. For groundwater droughts three variables are analysed: recharge, groundwater level and groundwater discharge (Tate & Gustard, 2000; van Lanen & Peters, 2000). These represent the inflow, storage and outflow of the groundwater reservoir. Also some other exposures of groundwater, like the extent of saturated areas or the surface area of wetlands, could be included. Recharge and groundwater discharge cannot be measured directly, but have to be derived from other measurements or have to be simulated. This makes them more sensitive to errors. Groundwater levels characterise the present storage and they can be measured directly with reasonable accuracy and frequency. Indirectly the spatial and temporal aspects of groundwater levels provide knowledge about groundwater recharge and discharge. The absolute value of the groundwater storage is usually not interesting, unless extreme storage depletion occurs (serious overpumping or mining of fossil groundwater), and is also difficult to assess (van Lanen & Peters, 2000).

3.3.2 Temporal resolution

Hydrological droughts are often out of phase with both meteorological and agricultural drought (Wilhite & Glantz, 1985). Within the hydrological drought sequence groundwater is the last to react to a drought situation (figure 11), unless surface water is mainly fed by groundwater. In the latter case surface water and groundwater droughts will occur more or less simultaneously. The lag between a meteorological drought and a hydrological drought may amount to months or even years. Unfortunately groundwater storage also recovers slowly, which means that the effects of a groundwater drought may be felt long after the meteorological drought has ended.

Because of these slow reactions, only major meteorological droughts will finally show up as a groundwater drought, in particular in case of groundwater systems that are subject to large storage differences. Therefore, the time step to be used in the analysis of a groundwater drought will necessarily be large, usually more than a week or a month. When long time steps are used, special care should be taken in defining the start and end of the time step. For example, when analysing groundwater levels, Marsh *et al.* (1994) use a ‘groundwater year’, which in the UK is conventionally defined as the first day of August to the last day of the following July. This topic is further addressed in section 5.5.

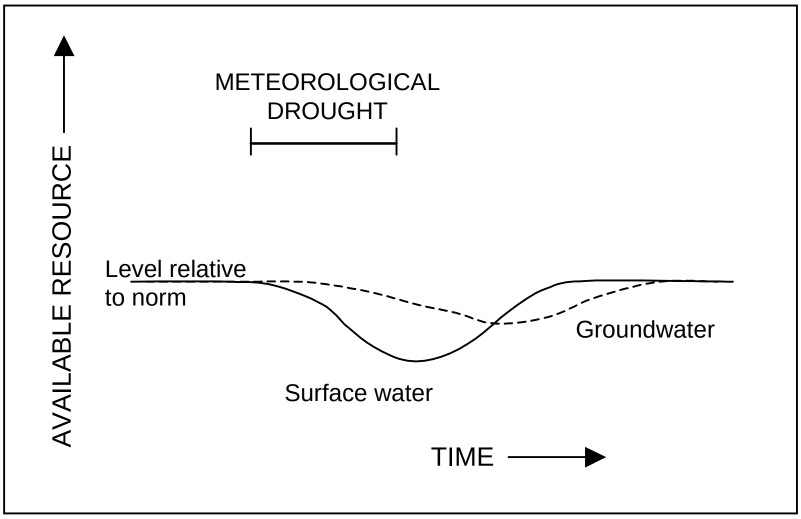


Fig. 11 The response of groundwater to drought (Robins *et al.*, 1997)

3.4 Socio-economic drought

J. Alvarez and T. Estrela

After reviewing meteorological and hydrological drought definitions, some comments are made concerning water resources planning and management aspects. Considering the existing water system formed by water conveyances, reservoirs for surface storage and aquifers, socio-economic droughts can be defined as failures in water supply when demands are not satisfied. Water planning and management use the hydraulic system together with estimations of natural water resources and demands to deal with shortages. Therefore, system failures are due to hydrological causes but also to water planning and management practices (Sánchez *et al.*, 2000).

Demands are of major importance constraining the availability of water. Often a maximum value of demand coincides with minimum availability of natural resources. Also, the estimation of demands is difficult. Requirements for domestic use, irrigation, industrial use, energy production, recreational uses and environmental purposes involve uncertainties in their allocation, quantity and time variability, consumption and growth rates.

Water planning is focussed on minimising the expected values of water system failures or socio-economic droughts. Different variables to characterise system capacity to overcome a water shortage are guarantee, resilience and vulnerability (Estrada, 1994). These definitions can be correlated with classical drought variables as frequency, severity, duration and intensity.

Guarantee can be defined in terms of the period of time the system persists without failure with respect to the total time. Thus, it describes frequency or probability of safe yields. Resilience is defined as the rate of progress to recover from a failure situation. It is equal to the inverse of the expected failure duration. Vulnerability is related to the severity or deficit in water supply. As a reference, the expected value of maximum severity per drought or the maximum deficit registered may be used. Another variable applied to describe system characteristics to control droughts is volume guarantee. It is defined as the rate of demand that can not be satisfied during a period.

The primary objective of water resources management is the identification of system measures and activities aiming at the maximum fulfilment of present and future water requirements for any use (Tsakiris & Todorovic, 1995). It involves handling a large amount of information about evolution and location of demands and water supplies. The actual status of water systems may be considered by means of water storage and river flows. Groundwater storage may be considered via base flows and/or the evolution of piezometer levels in hydrographs. Once demands are estimated in present and future periods, some rules to safely manage the system may be applied. The definition of such rules comprises a complex problem for water studies dealing with questions as when rules have to be implemented, priorities of use, rates of restriction, prediction and the stochastic nature of the variables involved.

4. Regional drought definitions

H. Hisdal, L. M. Tallaksen, M. J. Santos, R. Veríssimo and R. Rodrigues

The previous chapter highlight different ways of characterising meteorological and hydrological droughts for single sites or catchments. Droughts are regional in nature, and it could be argued that a drought event definition should include the areal aspect. The consequences of a drought are certainly influenced by the extent of the area affected by it. A distinction between point/at-site droughts considering only a fixed point in space or a very small region, and regional droughts should be made (Santos, 1983).

In his drought analysis of monthly precipitation, Tase (1976) introduced the regional aspect by generating new samples of monthly precipitation at a systematic grid of points. The threshold level method was then applied within each grid-cell. Three areal drought characteristics were selected. For a given truncation level, σ_0, and a number of grid-cells, n, these indices at time t were defined as:

The *deficit area* being the number of grid-cells with precipitation below a certain threshold:

$$A = \sum_{i=1}^{n} I_{(\sigma \le \sigma_0)}(\sigma_i) \tag{3}$$

The *total areal deficit* being the sum of drought deficit volumes in the drought affected grid-cells:

$$D = \sum_{i=1}^{n} (\sigma_0 - \sigma_i) I_{(\sigma \le \sigma_0)}(\sigma_i) \tag{4}$$

The *maximum deficit intensity* being the maximum deficit volume in one grid-cell:

$$Int = \sigma_0 - \min(\sigma_1, \sigma_2, ..., \sigma_n, \sigma_0) \tag{5}$$

where $I_{\sigma \le \sigma_0}(\sigma_i)$ is an indicator function described by:

$$\begin{aligned} I_{(\sigma \le \sigma_0)}(\sigma_i) &= 1 \qquad \text{if } \sigma_i \le \sigma_0 \\ &= 0 \qquad \text{if } \sigma_i > \sigma_0 \end{aligned} \tag{6}$$

In Santos (1983) the areal extent of a drought is included into the drought event definition by introducing a critical area as a second threshold. The study is carried out on annual precipitation, assuming each precipitation station to represent a fraction of the total area. So called “auxiliary variables” and regional drought characteristics are introduced. The auxiliary variables are defined to be:

- Proportion of instantaneous deficit-area (defined equivalent to eq. (3)).

- Proportion of instantaneous drought-affected area. Here a critical area is taken into consideration. Unless the critical area is exceeded, the proportion of drought affected area is zero.
- Instantaneous regional areal deficit (defined equivalent to eq. (4)).
- Instantaneous deficit-area areal deficit. This variable gives the mean of the total areal deficit for a fraction of the area.
- Instantaneous drought areal deficit. The variable describes the mean amount of 'missing' water over a region if the deficit area is greater than or equal to the critical area.

The auxiliary variables are used to define the following regional drought characteristics:

- Regional drought duration. The length of the time interval where the drought covers a fraction of the area that is larger than or equal to the critical area.
- Total regional areal deficit. The total deficit volume over the time interval where the drought covers a fraction of the area that is larger than or equal to the critical area.
- Proportion of temporal drought area. The average drought area over the time interval where the drought covers a fraction of the area that is larger than or equal to the critical area.
- Intensity. This is the total regional areal deficit divided by the regional drought duration.

An application of a regional drought definition can be found in (Henriques & Santos, 1999). The threshold level method is used within elementary areas. Drought occurs when the value of the variable is less than a fixed threshold, σ_0. The stepwise selection of adjacent elementary areas (neighborhood) in drought is represented in figure 12. A drought event starts in the nucleus with maximum drought severity (according to eq. 5). The spread of the drought can be obtained by identifying drought affected areas adjacent to the nucleus. This selection envisages the enlargement of the core in detriment of disperse areas. Areas in drought are selected, until the whole region has been selected or the threshold is exceeded in all adjacent elementary areas ($\sigma > \sigma_0$).

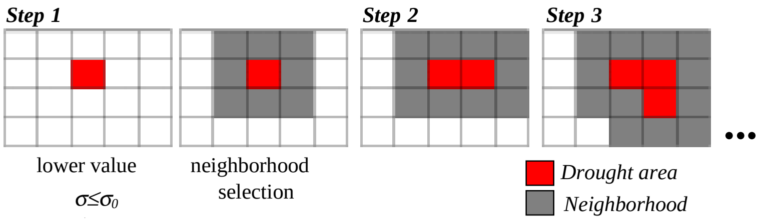


Fig. 12 Stepwise selection of adjacent elementary areas in drought

A critical area can then be introduced next by only considering droughts affecting a certain percentage of the total region under study. Different aspects of this method are further discussed in section 5.2.

5. Event definitions applied within ARIDE

5.1 Activities “Initial time series analyses” and “Regional drought characteristics”

H. Hisdal and L. M. Tallaksen

The availability of water for environmental and industrial demands in Europe is controlled primarily by the variability of precipitation and the resulting river flow. Hydrological droughts in terms of streamflow deficits would mean periods when streamflow is not sufficient to supply established uses under a given water management system. In the ARIDE-project it was desirable to apply an event definition of direct relevance to the European water industry and environmental demands on river systems. The event definition chosen had to be applicable to the different climatic and hydrological conditions found across Europe. It had to account for site-specific conditions and special water management options, and be suitable for regional frequency analysis.

In many countries in Europe precipitation data are easier available than streamflow data. Precipitation has often been recorded for a longer time period and is more undisturbed by human influence than streamflow. Despite differences in precipitation due to orographic effects, precipitation is believed to perform more homogeneous than streamflow. Time-series of streamflow and precipitation thus supplement each other and it is important to compare spatial and temporal drought characteristics based on the two types of data. Therefore both meteorological droughts in terms of precipitation deficits and hydrological droughts based on streamflow deficits were studied.

5.1.1 Meteorological drought

Santos *et al.* (1983) summarise different meteorological drought indices; the k-th decile of long term mean annual precipitation, the maximum number of days without precipitation, Lang’s rain factor index, Martonne’s index of aridity, the PDSI and the variability of annual precipitation. The latter was found not to work for Portuguese conditions. It is in particular emphasised that the above mentioned indices do not necessarily lead to a quantitative drought analysis and do not distinguish between point and regional/areal droughts. “*Therefore it is a need for modelling mathematically the drought phenomenon and the variables that properly describe it. Such modelling must be stochastic since drought occurrence and characteristics depend clearly on a number of factors, some of them not completely known and others not even considered.*” This conclusion and the need to compare with streamflow drought constitute the background of the choice of meteorological event definition applied in the activity "Regional drought characteristics".

Effective precipitation as defined in section 3.1.3 would allow the derivation of drought indices fulfilling the requirements above. However, an exact calculation of the effective precipitation requires measurements of the evaporation loss. In practice often a fixed, average monthly or annual evaporation loss is estimated. Hence, the method can be regarded as equivalent to the threshold level method. The drought can be characterised by its duration and deficit volume with respect to some critical threshold level, similar to the definition of hydrological droughts below. The rainfall deficit at a particular time is defined as the difference between threshold level and observed precipitation. Total deficit is given as the accumulated deficit over the drought period.

Even if the threshold level method provides an objective definition of drought, subjective choices have to be made including the choice of:

- threshold level
- application of annual maximum series (AMS) or partial duration series (PDS) (see section 3.2.1)
- seasons
- pooling method (if a daily time resolution is applied)

The threshold level method was applied to select drought events based on monthly precipitation data from Denmark. A division into seasons was not needed as the average monthly temperature in Denmark rarely falls below zero. Based on the observed monthly precipitation, new series were generated at a systematic grid of points by applying an empirical orthogonal function transformation in combination with kriging. Thereafter the threshold level method (applying the 80 percentile) was applied within each grid-cell. The chosen threshold gave 2.8 events per year on average. The study included all droughts, hence the PDS were studied. The method is similar to the one applied by Tase (1976) and Krasovskaia & Gottschalk (1995) as described in chapter 4. The area covered by drought was calculated by summing up the grid-cells with precipitation below the threshold. Taking the area aspect into consideration allowed the derivation of severity-area-frequency curves (illustrating the probability of a certain area to be covered by a drought of a specific severity).

5.1.2 Hydrological drought - streamflow

The event definition applied for hydrological drought also has to permit a quantitative analysis and be relevant for a comparison with meteorological droughts. The threshold level approach fulfils these requirements and provides an objective definition of droughts that forms the basis for characterisation of regional or large area droughts. This drought definition is therefore applied in the activities “Initial time series analyses” and “Regional drought characteristics”.

As for precipitation the choice of threshold level, AMS or PDS, seasons and pooling procedure had to be considered. Tallaksen *et al.* (1997) and Kjeldsen *et al.* (2000) address these problems and present different solutions as how to deal with them. Based on their conclusions and supplementary analysis performed within the ARIDE project, the following paragraphs summarise the choices made. The evaluation was done based on the presence of minor droughts, multi-year droughts, mutual dependence and the total number of events selected.

It is recommended to use a threshold between Q90 and Q70 for a monthly or daily time resolution. A fixed threshold level emphasises the annual low flow period, a fixed but seasonal variable threshold level allows the year to year variation of a low flow period to be evaluated, whereas a variable threshold level focuses on the deviation from normal runoff, the anomalies. In the activity “Initial time series analyses”, where trends in the severity and frequency of droughts across Europe were studied, a threshold Q70 (fixed for the summer season) was chosen to minimise the problem of zero drought years. The same argument applies for the activity “Regional drought characteristics” where droughts based on daily and monthly streamflow in the Nordic countries and the Iberian Peninsula were compared to depict regional differences.

In the "Initial time series analyses" the following drought characteristics were studied: drought deficit volume and duration in AMS, and annual accumulated drought deficit volumes and duration as well as the annual number of droughts in the PDS. Prior to the selection of AMS and PDS the pooling procedure moving average 11 days (MA11) was used. In the "Regional drought characteristics" both AMS and PDS were studied and MA10 was applied whenever a daily time resolution was studied. A detailed case study comparing the AMS and PDS approach is described in Engeland *et al.* (2000).

Europe has a large variation in river flow regimes. In snow and ice affected regions the year has to be divided into a winter and a summer period. The start of the summer season is defined at the termination of the spring flood and it is logical to end the summer season before the temperature falls below zero. A special problem arises when a summer drought continues into a winter drought without any clear distinction between them. In Europe the climate would normally imply high precipitation in autumn and winter. Thus, in the Nordic region and the Alpine regions in Europe a summer drought continuing into the winter season would normally be caused by low temperatures and precipitation falling as snow. A summer drought could therefore be terminated at the beginning of the winter season even if the flow is still below the threshold. A detailed description of the procedure chosen is given in Hisdal *et al.* (2001). This approach was chosen both in both activities. In those regions in Europe where droughts can occur due to precipitation being stored as snow, only the summer droughts were studied.

5.2 Activity “Regional drought distribution model”

M. J. Santos, R. Veríssimo and R. Rodrigues

This activity involved the application of a statistical model developed for the description of regional drought (Santos, 1996; Henriques & Santos, 1999). The objective of the regional drought distribution model is to calculate drought severity through the spatial integration of drought affected areas. Drought occurs when the value of a variable (e.g. precipitation or streamflow) is less than a fixed threshold. This method can be used to separate severe droughts from less severe using a specific methodology for regional extreme-value analysis.

The application of the regional drought distribution model assumes that the variables are independent and identically distributed. Long-term series with the same length associated to so-called elementary areas are the basis data requested for running the model. The normal distribution is obtained using a regional Box-Cox parameter for skewness correction. This influences the definition of the regions when large areas are studied.

A drought event is represented in figure 13. In the drought nucleus (elementary area) corresponding to the lowest area coverage of the region, drought severity has the highest values. A severity calculated for larger proportion of the region is lower since it represents the value of the variable weighted over the elementary areas considered. The final objective of applying the model is to compare historical droughts with severity-area-frequency curves and associate them to the return period of a regional drought. In figure 13 the regional drought observed in 1974/75 is associated to a return period of about 25 years.

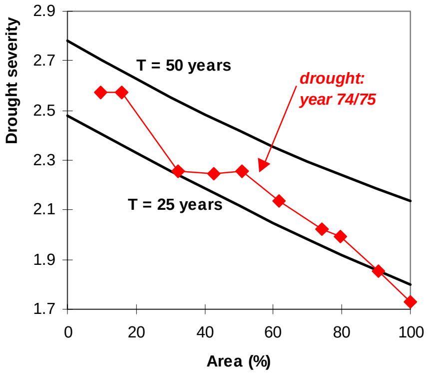


Fig. 13 Evaluation of the return period T of a regional drought event with the regional drought distribution model

The application of the regional model involves an initial definition of:

- The threshold level
- The critical area for extreme-value analysis
- The critical area for historical drought analysis

The selection of the threshold level influences the calculated return levels. In the next section the result of applying different percentile from a duration curve is presented for annual precipitation. The introduction of a threshold for the area – the critical area – has two objectives. The first one is to guarantee a selection of droughts covering a large proportion of the elementary areas for the severity-area-frequency curve parameter estimation. The second is for the evaluation of historical droughts. In the latter case, the use of a high critical area ensures that events are selected that affected most of the region. For these two objectives different critical areas can be applied. Examples are given in the following.

5.2.1. Threshold levels

The threshold level only influences the highest deficit values (high standardised values, corresponding to low absolute deficit values). If a high threshold is considered (e.g. the 70 percentile) high standardised values are used in the drought analysis, resulting in a selection of more and less severe droughts. Less severe droughts are the ones associated to low return periods (lower than 5-10 years). In figure 14 the result of using different thresholds is presented.

The use of different thresholds also influences the severity-area-frequency curves obtained. The example presented in figure 15 for Scandinavia and Italy shows the difference in the curves for 5-year and 100-year return periods using different thresholds, reflecting the influence of low absolute values of standardised precipitation.

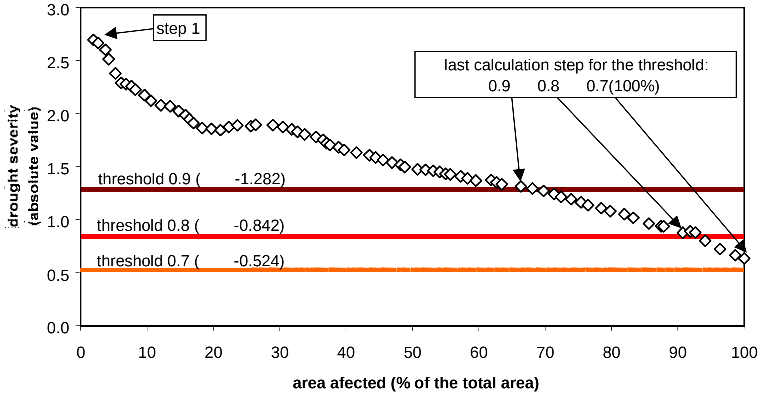


Fig. 14 The use of different threshold levels in the regional model

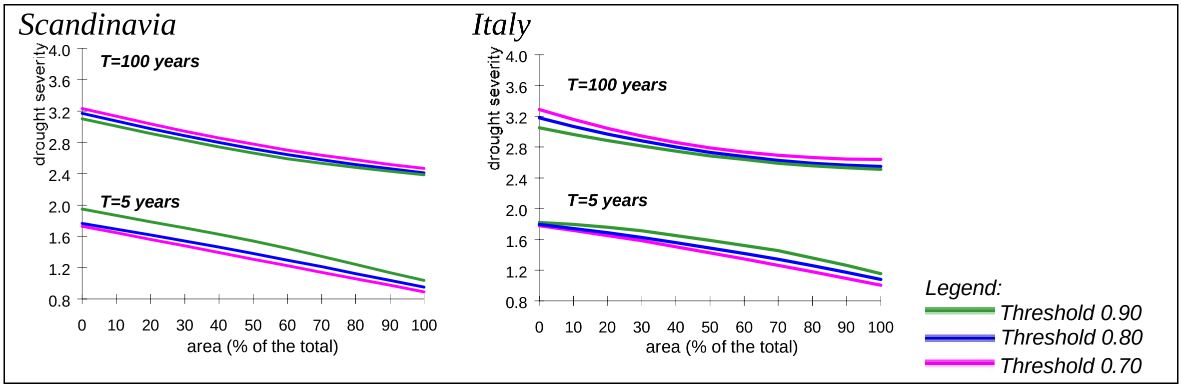
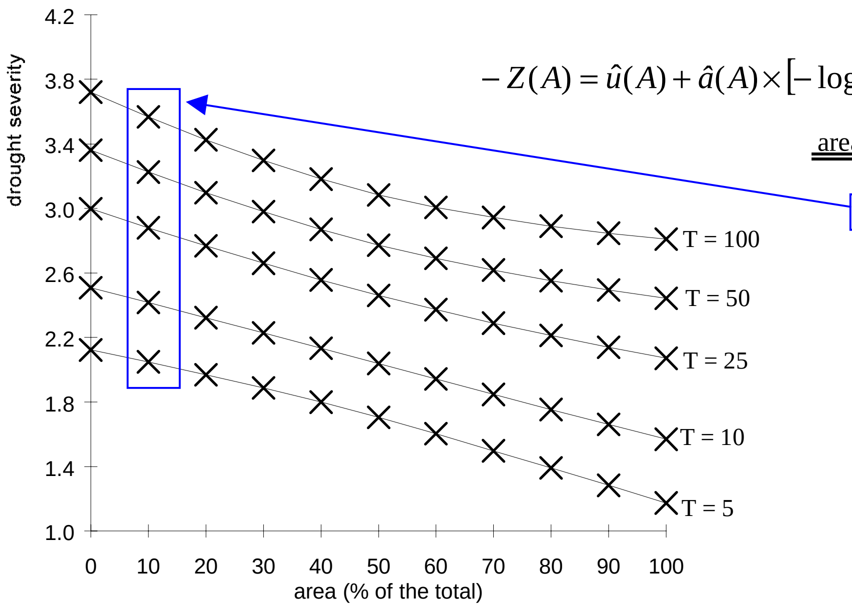


Fig. 15 Comparison of the severity curves obtained for the thresholds represented by the exceedance probabilities 0.70, 0.80 and 0.90.

5.2.2. Regional extreme-value analysis

The evaluation of a regional drought is made through calculation of parameters from severity-area-frequency curves. Regional droughts affecting a proportion of the region larger than a chosen critical area, are selected. A critical area of about 90% of the total region is usually considered in order to exclude values very close to the threshold. The severity-area-frequency curves for the region defined as Alps are presented in figure 16. The extreme-value distribution is fitted for each 10% of the total area. Z is the standardised variable, A is the proportion of the total area, and $\hat{u}$ and $\hat{a}$ are the parameters of the extreme-value distribution.

The use of elementary areas of different sizes (e.g. defined by basins or Thiessen polygons) makes it necessary to interpolate the severity in the defined areas. Interpolation examples are presented in figure 17. The areas corresponding to 0, 10, 20,…,100% of the total region (figure 17) are the ones applied in the extreme-value analysis. The application of the model to spatially interpolated data eliminates the need to interpolate the severity, since the region then can be built up of elementary areas with the same size.



$$-Z(A)=\hat{u}(A)+\hat{a}(A)\times\left[-\log(-\log(1-1/T))\right]$$

area A (%)	û	$\hat{a}$
0	1.584	0.469
10	1.529	0.447
20	1.459	0.430
30	1.374	0.421
40	1.275	0.418
50	1.162	0.422
60	1.036	0.431
70	0.896	0.447
80	0.749	0.467
90	0.598	0.491
100	0.443	0.516

Fig. 16 Severity-area-frequency curves

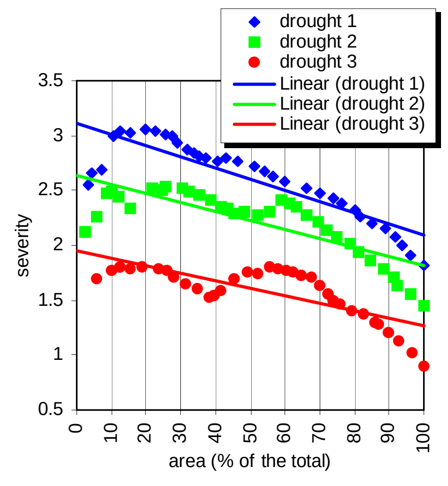


Fig. 17 Calculation of severity-area-frequency curves using areal interpolation

5.2.3. Sequential droughts

An analysis of droughts lasting more than one time unit was made for the transformed variable calculated for the total area in drought. This drought severity can be compared for the area effectively involved or a critical area can be used in order to separate local from regional events. In the latter case a drought is only considered if a defined critical area is affected.

In figure 18 an example for Western France considering annual precipitation is presented. A critical area of 75% of the total region is applied. Droughts affecting the total region can be observed for six years. Only one two-year drought event covering the total region is seen, 1971/72-1972/73. The return period of this drought can be obtained for the total area by the transformed standardised precipitation. The drought probability occurrence can be calculated for the two-year drought since the sum of drought severity calculated in the total area can be considered normally distributed, N(0,2).

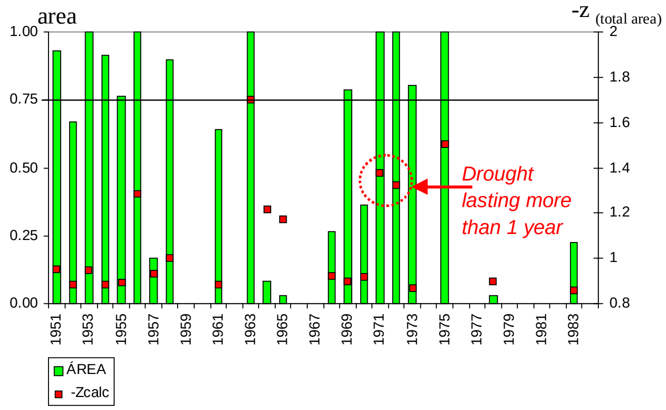


Fig. 18 Drought analysis in sequential years in Western France

5.3 Activity ”Atmospheric circulation and drought”

K. Stahl and S. Demuth

The event definition used in this activity considers periods of streamflow deficiency defined as a departure or anomaly from the ‘normal’ seasonal low-flow range. The method was developed as a modification of the threshold level approach and determines periods below a threshold cycle, which consists of the exceedance probabilities (e.g. 90%) of daily flow duration curves. There are several reasons, why such a relative approach was adopted.

- The method can be applied and allows a comparison across Europe, which covers a great variety of hydrologic, geographic and climatic regions. The resulting streamflow deficiency periods are derived as departures from the typical flow regime.
- Besides for instance a snow season, there might be other regular fluctuations in the annual streamflow regime to which nature and water resources management have adjusted over decades. It is not the regular (and expected) summer low flow period, which causes problems, but any deviation from that normal range.
- For the correlation of drought with preceding atmospheric circulation, which is the task of this activity, daily time series of a streamflow deficiency signal are required.
- Deviations during the high flow season might also be important for the drought development. For instance in activity "Groundwater droughts", it was shown that if the recharge during the recharge season is lower than usual, a groundwater drought is

> probable to develop the following summer. This missing recharge is also detectable in the lower than usual streamflow during the recharge season, caused by the same lack of rain, which again is due to unusual atmospheric circulation patterns during that time.

The variable threshold level approach defines streamflow anomalies according to equation 1 in section 3.2.1. The choice of the window length was evaluated. The goal was to find a balance between the shortest possible window to maintain the typical yearly singularities, and a sample large enough to determine the discharge percentiles for each day and smoothed enough to allow longer ‘drought periods’ to develop. The minimum sample size to determine the flow duration curve for a day should be about 300 values. For a 30-year dataset, window sizes between 10 and 30 days are suited to determine a variable threshold. Finally, a 11-day window, with 5 days proceeding and 5 days following the day of interest was adopted.

An example for the Brugga catchment in Germany applying a 21-day moving window is shown in figure 19. The daily flow duration curves derived from a 29-year time series are shown in figure 19 a). Some examples of the resulting annual percentile cycles, which can be used as threshold level, are plotted in figure 19 b). The catchment has a high seasonality with higher flows in spring due to snowmelt in the high altitudes of the Black Forest Mountains and a low flow period in late summer. In the European Water Archive (EWA) series (Rees & Demuth, 2000), the variability of the annual cycles for the high percentiles (low flow) ranges from highly fluctuating to almost constant.

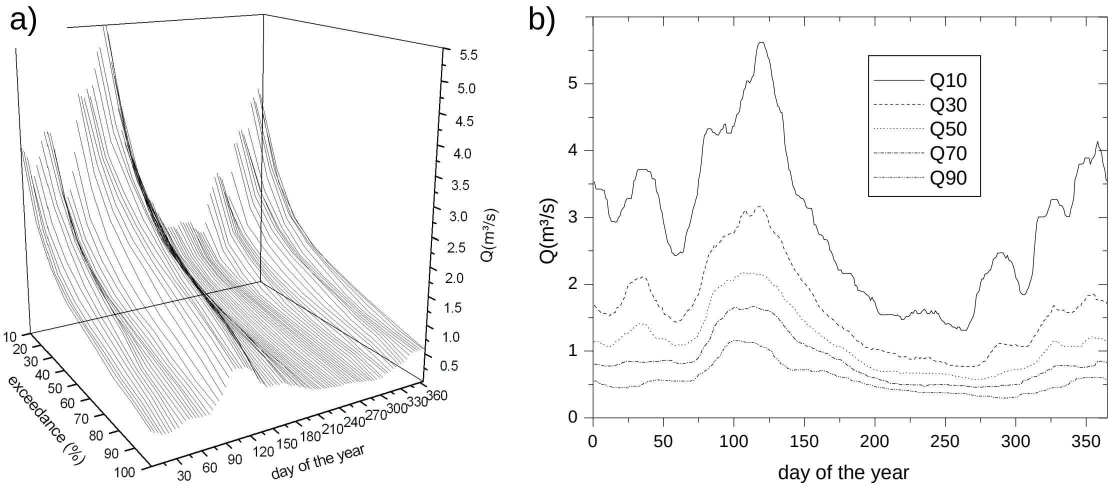


Fig. 19 a) Daily flow duration curves (for displaying purposes only every 4th curve is plotted) and b) Annual exceedance percentiles from a), which can be used as variable thresholds.

Some derived parameters of the variable threshold method are shown in figure 20. For instance, a spring anomaly (marked black) indicates a winter with less snow and thus lower recharge of the groundwater reservoirs. Such a situation may then cause a summer drought to develop. Examples of spring anomalies can clearly be seen in figure 20 a), e.g. the years 1973-76 and 1990.

Generally, it was found that the annual parameters (cumulated duration, number of events and annual maximum duration, figure 20 b) show the same severe drought years, no matter whether a fixed or variable threshold is applied. However, the anomaly sometimes occurs in a different season, often prior to the extreme absolute low flow period.

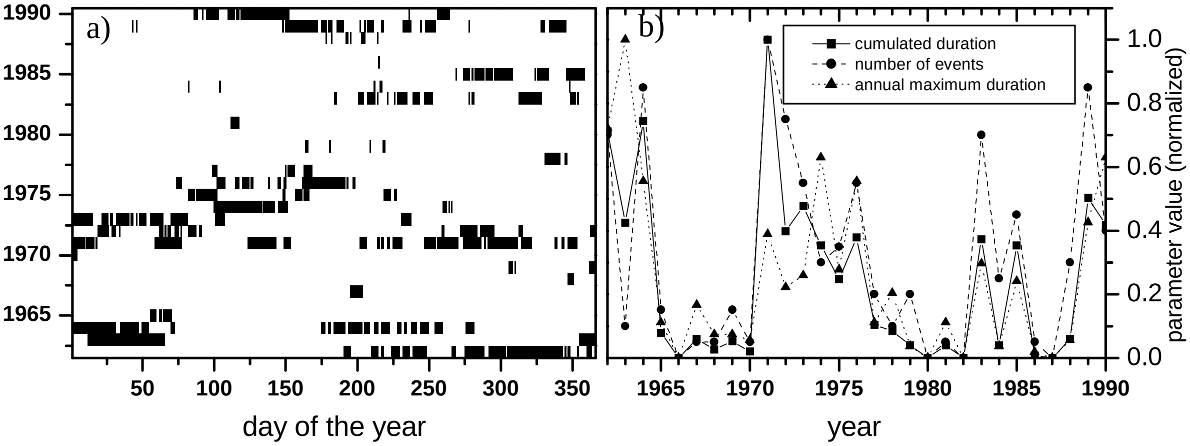


Fig. 20 a) The daily streamflow anomaly indicators and b) Different annual parameters derived with a variable Q90 as threshold

It can therefore be concluded that two major characteristics are captured by a time series of anomaly periods, calculated with the variable threshold level approach:

- an almost direct (just slightly lagged) response to the meteorological situation and
- the history of the natural storage system compared to an average year

5.4 Activity ”Drought visualisation”

M. Zaidman and G. Rees

In the activity "Drought visualisation" a variable threshold is chosen. The daily flow exceedances are calculated according to equation 1 applying a 31-day moving window. The flow of a particular day can be considered as a departure from the mean (the mean can be considered as a threshold level). Further, the typical flow for a particular day of the year can be determined by calculating the mean of the flows on that day for all years on record.

Expressing a flow, as a departure from the mean is a good way of comparing flows in different regimes and of different record lengths. This departure, or *flow anomaly*, can be expressed in a number of ways, for example as a percentage of, or standardised by, the mean flow for that day. Also, a standardisation procedure, in which gauged daily flows are modified to account for the station mean flow and statistical distribution type of the sample set, was adopted. Flows were log-transformed to produce a normally distributed data set (flows generally conform to a log-normal distribution because of erratic high magnitude events) and then normalised. A daily ‘flow anomaly’ value drawn from this population therefore provides a numeric measure of departure (in standard deviations) from the mean flow. For any given day of the year (*d*) the standardised flow anomaly, is given by:

$$A_d = \frac{(\overline{\log Q_d} - \log Q_d)}{\sigma_s} \tag{7}$$

Where A_d, is the standardised flow anomaly on day *d*, Q_d is the flow on day *d*, $\overline{\log Q_d}$ is the mean of the series of log-transformed flows for day *d* and σ_s is the standard deviation of the series of log-transformed flows for day *d*.

Where the flow is close to ‘average’ levels, the flow anomaly is close to zero; where conditions are drier than usual, the anomaly is positive; and where it is wetter than average, the anomaly is negative. In normal conditions the flow anomaly is likely to range between –1 to 1 (i.e. falling within one standard deviation of the mean) but would become increasingly positive as flows fall further below the mean, and vice versa. For instance, an anomaly value of 1.65 is approximately equivalent to the 95th percentile flow (Q95), an anomaly of 2.0 to the Q98 flow and an anomaly of 3.0 to the Q99.87.

5.5 *Activity “Groundwater drought”*

L. Peters and H. van Lanen

The choice of a specific event definition for groundwater drought has been based on two criteria: the purpose of the definition and the representation of specific characteristics of groundwater drought. The event definition is designed to analyse the development of historical groundwater droughts and to derive probability distributions for future conditions. The comparison with streamflow drought and meteorological drought is also very important. The drought event definition should therefore be consistent to the drought event definitions applied to these droughts, and it was concluded that a threshold level approach would be preferable.

Two important characteristics of groundwater flow are persistence and retardation, and it is important that the drought event definition chosen takes these characteristics into account. Persistence in groundwater flow means, for example, that there will be a tendency for fewer, but longer droughts compared to meteorological droughts. Retardation means that the reactions in groundwater are delayed in time.

The causes for groundwater drought are twofold: building up of a soil moisture deficit during summer and the lack of rainfall during the subsequent winter (or any other wet season). In temperate climates a soil moisture deficit is built up during summer because evapotranspiration is higher than precipitation. This deficit has to be replenished at least partly before recharge starts in winter. The soil moisture capacity of the soil, which determines the amount of deficit that can be built up, is therefore an important factor influencing groundwater droughts.

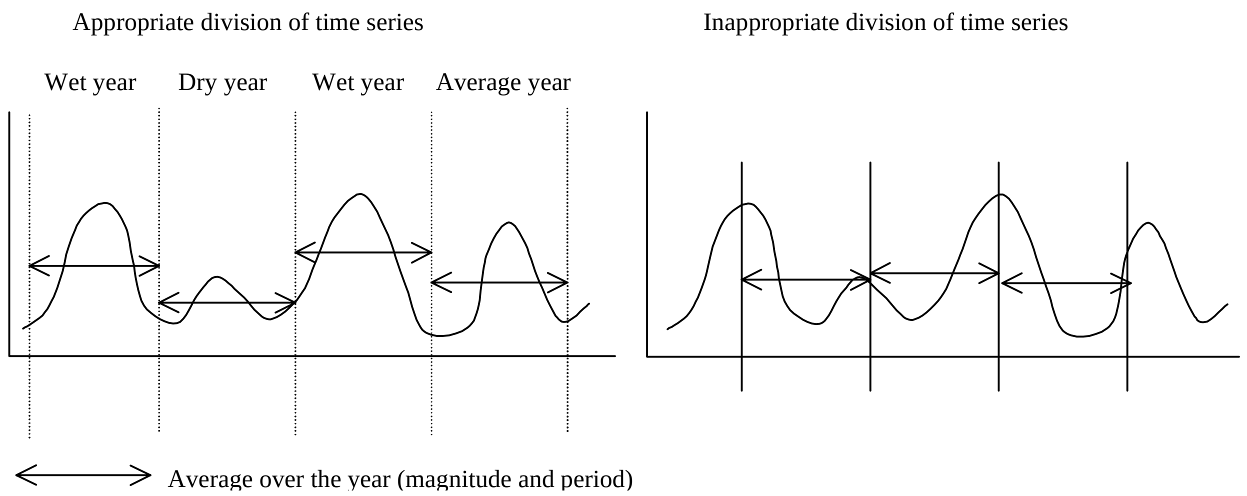
As explained in section 3.3 groundwater droughts can be identified using three variables: recharge (I), groundwater levels (φ) and discharge from groundwater to the surface water system (Q). Groundwater discharge can seldom be measured directly (except for example in springs) and therefore often streamflow is analysed. In dry periods this is usually a good approximation of groundwater discharge. The choice of temporal resolution will first be elaborated followed by a discussion on the event definition for monthly recharge, groundwater level and groundwater discharge.

5.5.1 Temporal resolution

In most catchments with deep water levels the influence of individual rainfall events is not noticeable in the groundwater level (or recharge). Only seasonal influence and sometimes only inter-annual variations can be traced in the time-series of recharge and groundwater level. Hence, only major meteorological droughts effect the deep groundwater system. Therefore the interest will mainly be on longer time scales: months or years. If the interest is primarily in multi-year droughts annual data should rather be used (Tallaksen *et al.* 1997).

The main argument in favour of the use of an annual data (besides the interest in multi-year droughts) is the persistence of groundwater droughts as explained above. The summer and subsequent winter are linked by the build up of a soil moisture deficit during the summer and replenishment in the early winter. The main problems when performing an annual analysis is the need to have a long time series (>30 years) and the difficulty in defining an appropriate start and end of the groundwater year. The latter is illustrated in figure 21. Here we can see that dividing a sequence of wet-dry-wet years inappropriately results in a sequence of three average years (figure 21, right). If the timing of the main peak occurs around the same time every year, then an appropriate division can be selected (figure 21, left). But the same division for the groundwater year (all three variables) may be hard to define, as the timing of the peaks is highly variable both in space and time. This means that the defined groundwater year is not appropriate for all variables on all locations. In addition the timing of the peak can vary temporally. In this activity it was decided to use only one groundwater year definition, because varying the start and the end of the year over the years could create a lot of confusion and complicate the interpretation of the results. Based on the timing of the main recharge event a groundwater year has been defined to last from 1 October to 31 September.

The main problem with a monthly analysis is the fact that all three variables show seasonal variations that do not coincide. Therefore the three variables are discussed separately.


Appropriate division of time series

Inappropriate division of time series

Fig. 21 Example of an appropriate and inappropriate division of a time series

5.5.2 Groundwater recharge

The difficulties in an annually based analysis were discussed in the previous section. This section only addresses the monthly analysis. Recharge has some specific characteristics, which are important for the event definition:

- Recharge can both be positive and negative in catchments with shallow water tables, unlike rainfall or discharge.
- Recharge has a very strong seasonal variation
- Winter recharge is generally most important because it largely determines the replenishment of the groundwater storage and fluctuations in groundwater level.

Several definitions were tested and the definition that predicts droughts in the groundwater level most accurately is considered the best. The following approaches were considered:

(i) Recharge (*I*) classified according to percentiles. This approach was applied to select recharge droughts. The recharge was only corrected by the offset to assure that all values have the same sign.

(ii) Deseasonalised recharge series, *I'*: Before classifying according to percentiles, the seasonality was removed according to:

$$I'_{i,j} = \frac{\left(I_{i,j} - \bar{I}_j\right)}{\sigma_j} \qquad (8)$$

where:

$I_{i,j}$ is the recharge in month j and year i (mm)

$\bar{I}_j$ is the average recharge in month j (mm)

σ_j is the standard deviation in month j (-)

In this case the anomalies were analysed rather than the droughts. A variable threshold was not tested here because it is virtually identical to the deseasonalisation.

(iii) The Sequent Peak Algorithm (SPA) as explained in section 3.2: The recharge (I_t) is used to fill a semi-infinite reservoir (Kendall and Dracup, 1991). At the start the reservoir is completely full (zero deficit volume, $D^*_0=0$). For each time step the deficit (D^*_t) is calculated for a specified constant outflow (the desired yield, I_D). This is described as in equation 1, in the case of equidistant values:

$$D^*_t = \begin{cases} D^*_{t-1} + I_D - I_{t,} & \text{if positive} \\ 0 \quad , & \text{othervise} \end{cases} \tag{9}$$

The desired yield is equivalent to a threshold level and can for example be chosen as a percentage of the long-term average flow. In case of groundwater, the long-term outflow should be equal to the long-term inflow. It is then logical to let the average long-term recharge be the desired yield.

Figures 22, 23 and 24 show the recharge classified according to (i), (ii) and (iii) for the Pang catchment (UK) (one of three research catchments studied in this activity). On the y-axis are the months of the year, on the x-axis are the years 1960-1997. For each graph the range was divided into four classes (red for dry, green for wet) with an equal amount of months in each class. This means that the divisions between the classes are at the 75-percentile, 50-percentile and 25-percentile of the series under consideration: recharge (I) in figure 22, deseasonalised recharge (I') in figure 23 and deficit (D^*) in figure 24. In this way a good overview of the temporal distribution of the dry and wet periods is obtained. In figure 22 it is obvious that when a fixed threshold level is applied, nearly every year has a drought and recharge drops below the 75 percentile in summer or early autumn. Applying a fixed 75 percentile as threshold would not be an adequate representation of the droughts because only one of the causes of drought is reflected, namely the build up of a deficit volume during summer. The amount of rainfall in winter is not represented, because the recharge in winter will virtually always be over the threshold.

In figure 23 the results for the deseasonalised series are given. The difference is obvious. Instead of a drought every summer, the deviation (anomaly) with respect to the monthly average is given. This approach gives droughts, which are much closer to the droughts as would be expected from groundwater and discharge analysis. Figure 24 shows two versions of the SPA method, one where the desired yield is equal to the long-term average inflow and the other with an yield of 70% of the long-term average inflow (SPA0.7).

When the SPA method is implemented with long term average inflow as outflow (figure 24 a), the number of droughts reduces strongly compared to figure 22 and 23. Only two major droughts are identified. Such a high outflow (yield) apparently introduces too much memory. But when the outflow is reduced to 70% of the long-term average inflow, the results compare very well to the droughts identified in the groundwater levels (figure 25).

Based on this analysis it was decided to use the SPA0.7 for the selection of droughts in the recharge series with monthly resolution.

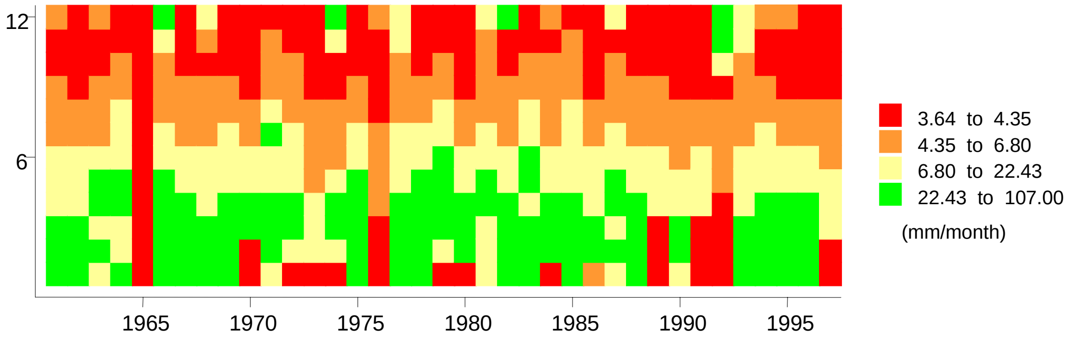


Fig. 22 Monthly recharge (*I*) (mm/month) (values below the 75-percentile are labelled red)

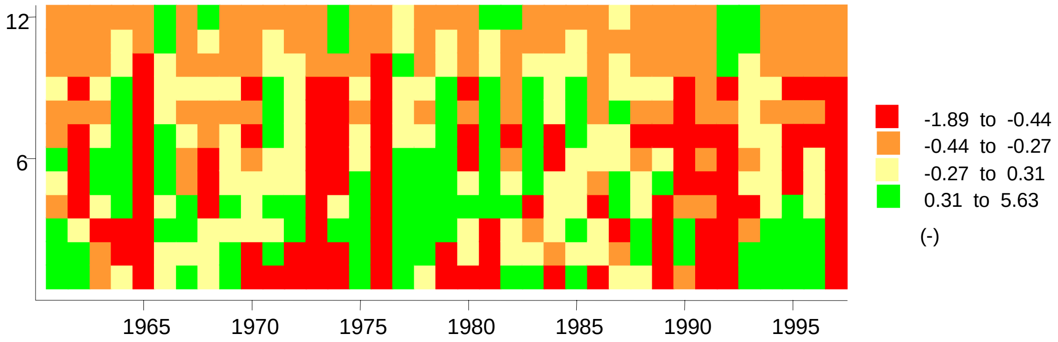
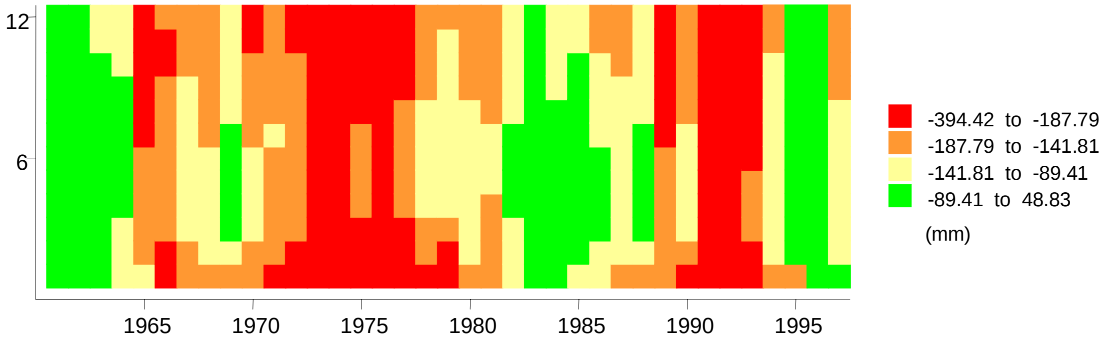
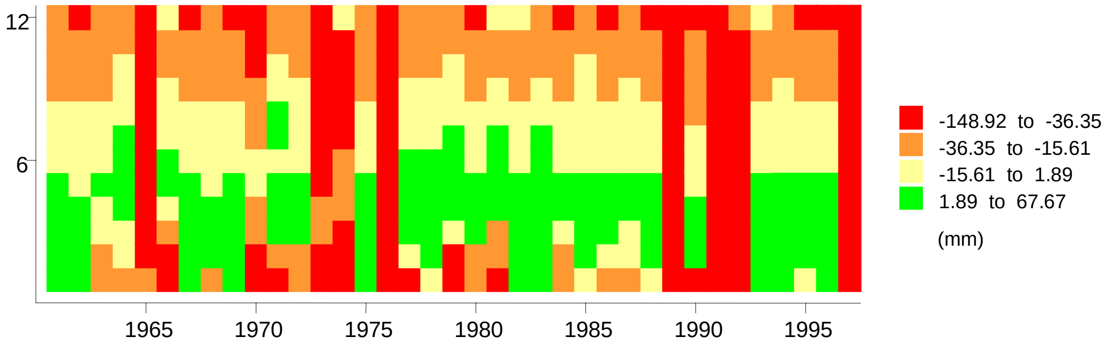


Fig. 23 Deseasonalised recharge (*I'*) (values below the 75-percentile are labelled red)



a) Outflow (desired yield) equal to long-term average inflow



b) Outflow (desired yield) equal to 70% of long-term average inflow

Fig. 24 Deficit (D^*) according to the SPA method (mm)

5.5.3 Groundwater level

Before discussing drought event definitions for groundwater level, it is important to notice that groundwater level is a state variable and not a flux like recharge, rainfall and streamflow. This means, for example, that the "deficit volume" calculated with the threshold level approach has to be interpreted in another way, namely as the cumulative departure from the threshold (van Lanen & Peters, 2000). Secondly, the analysis has been limited to deep groundwater levels, because they represent the state of a groundwater reservoir far better than shallow water tables. The variation of shallow water tables is often dominated by the variation of the water level in nearby surface water.

As the hydrograph of deep groundwater levels is usually rather smooth, problems of minor droughts and mutual dependence of droughts are of minor importance. Multi-year droughts and zero drought years are very common.

For groundwater heads basically the same three approaches as for recharge were examined. Only instead of the SPA approach the cumulative departure (CD) from a threshold level (φ_D) was used. Computationally this approach is similar to the SPA approach. The $\varphi 70$ was used as a threshold level.

$$CD_t = \begin{cases} CD_{t-1} + (\varphi_D - \varphi_t)\Delta t, & \text{if positive} \\ 0 & \text{, otherwise} \end{cases} \tag{12}$$

The best results were obtained for a fixed threshold level and the cumulative departure. An example of these results is presented in figure 25 and 26 for measured groundwater heads at a borehole (SU48/29) in the Pang catchment. This does, however, raise the question why the fixed threshold approach works well for groundwater levels, but not for recharge. Groundwater level fluctuations are for a large part the result of recharge. So it must be caused by a difference in nature between the two variables. This is illustrated in figure 27. In this chart recharge and groundwater levels for the years 1987-1992 are presented. This was a dry period. For the recharge we see this reflected in the low peaks of winter and spring recharge, for the groundwater level this is reflected in a declining trend. Because recharge lacks this memory effect, it is dominated by seasonal variation. Moreover the groundwater level can more or less decline without limits, while the recharge in summer is strongly limited by soil properties and water table depth, or in other words: the upward flux (capillary rise) in summer is necessarily small.

Although the fixed threshold provides quite acceptable results, it was decided to use the cumulative departure for two reasons. Firstly because the identification of the major droughts is clearer and secondly because the comparison with the recharge drought will be easier, as the same event definition is used.

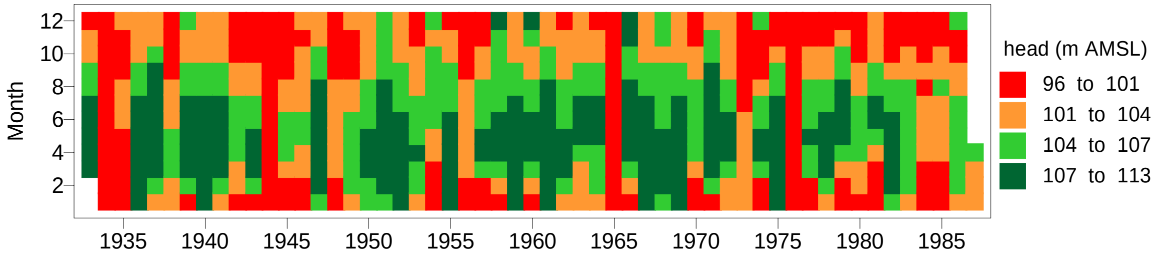


Fig. 25 Groundwater head (m AMSL) (below the 75-percentile, labelled red)

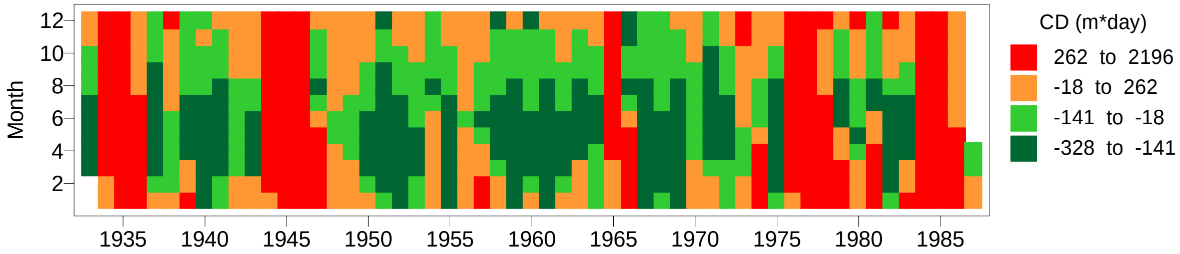


Fig. 26 Cumulative departure (*CD*) (m*day)

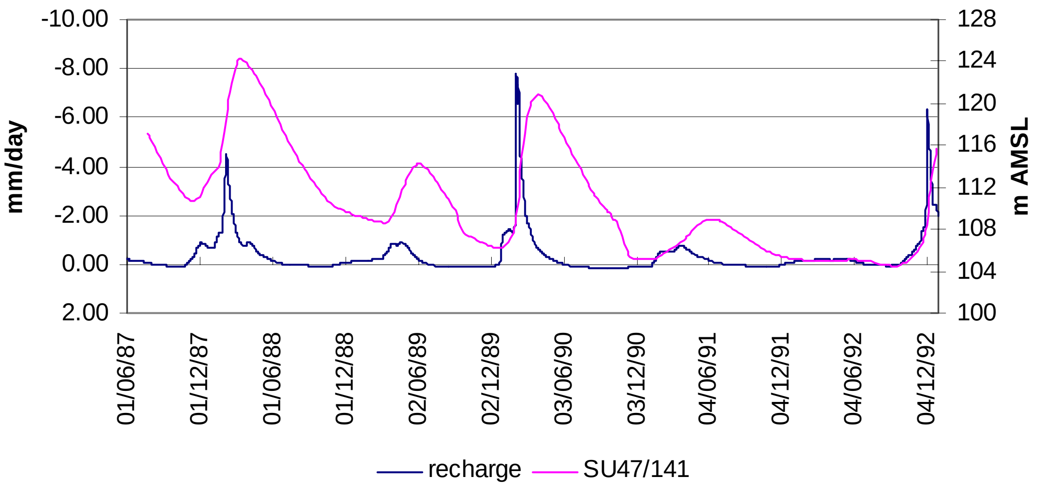


Fig. 27 Recharge and groundwater level (SU47/141) in a borehole in the Pang catchment (UK) for 1987-1992

5.5.4 Groundwater discharge

For the simulated groundwater discharge and measured streamflow not all definitions were tested. The intermittent nature of the streamflow at several gauging stations both in the Upper Guadiana catchment and in the Pang catchment (both included in this activity) made the application of a fixed threshold or deseasonalising impossible. In some cases, as happened in the case of recharge, Q70 was zero. Thus again the SPA approach was chosen as the most appropriate event definition. As outflow or yield either Q70 or 70% of the long term mean outflow was used. The latter was used when Q70 was zero. For some gauging stations the streamflow was zero for so long that the SPA approach resulted in droughts lasting for several years. This is illustrated in figure 28 for the simulated groundwater discharge at the most upstream gauging station in the Pang catchment (UK).

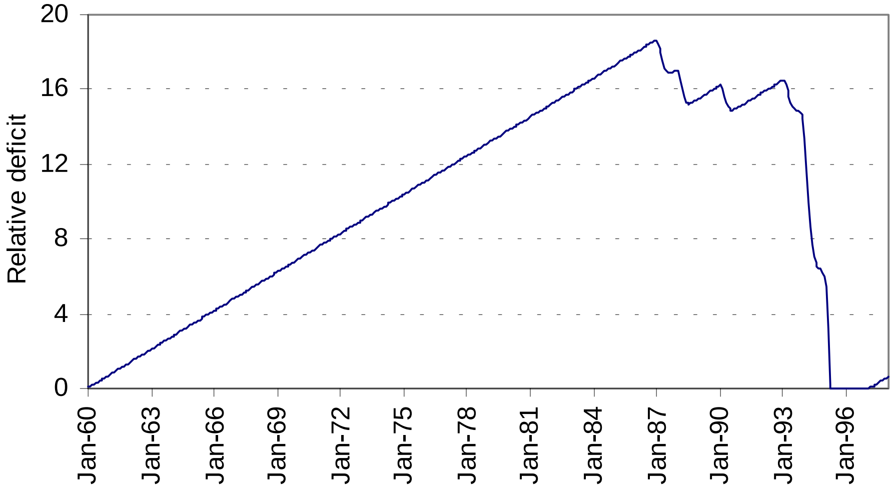


Fig. 28 Development of the deficit according to the SPA approach for the simulated groundwater discharge at Frilsham gauging station in the Pang catchment (UK)

6. Concluding remarks

H. Hisdal and L. M. Tallaksen

Within the ARIDE project it was shown that the threshold level method is applicable to define meteorological drought events in terms of precipitation deficits as well as hydrological drought events in terms of streamflow and groundwater deficits. However, both fixed and variable thresholds and different pooling procedures were applied depending on the purpose of the study. It is suggested to apply the term *drought* only if a *fixed* threshold is applied and rather use the term deficiency or *anomaly* if the selected variable is below a *variable* monthly or daily threshold.

It was recommended that wherever a fixed threshold level was applied within the ARIDE project, the threshold level should be a value obtained from the duration curve: preferable the 90, 80 or 70 percentile. The two events of summer and winter droughts should be analysed separately. If daily data are considered and a pooling procedure is required the MA(10), MA(11) or SPA is recommended.

The SPA method was shown to be especially applicable to define groundwater drought events based on time series of a monthly time resolution.

As droughts are regional in nature the area covered by a drought is an important drought characteristic. In ARIDE the areal aspect has been highlighted both for meteorological and streamflow droughts. Regional patterns are studied by visualising trends in droughts and drought behaviour in general. Further, methods for calculation of the area covered by a drought are applied and in one activity a critical area is introduced to select the most severe regional drought events.

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