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A global evaluation of streamflow drought characteristics

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Abstract

How drought is characterised depends on the region under study, the purpose of the study and the available data. In case of regional applications or global comparison a standardisation of the methodology is preferable. In this study several methods to derive streamflow drought characteristics are evaluated based on their application to daily streamflow series from a wide range of hydrological regimes. Drought deficit characteristics, such as drought duration and deficit volume, are derived with the threshold level method. When it is applied to daily time series an additional pooling procedure is required and three different pooling procedures are evaluated, the moving average procedure (MA-procedure), the inter event time method (IT-method), and the sequent peak algorithm (SPA). The MA-procedure proved to be a flexible approach for the different series, and its parameter, the averaging interval, can easily be optimised for each stream. However, it modifies the discharge series and might introduce dependency between drought events. For the IT-method it is more difficult to find an optimal value for its parameter, the length of the excess period, in particular for flashy streams. The SPA can only be recommended for the selection of annual maximum series of deficit characteristics and for very low threshold levels due to the high degree of pooling. Furthermore, a frequency analysis of deficit volume and duration is conducted based on partial duration series of drought events. According to extreme value theory, excesses over a certain limit are Generalized Pareto (GP) distributed. It was found that this model indeed performed better than or equally to other distribution models. In general, the GP-model could be used for streams in all regime types. However, for intermittent streams, zero-flow periods should be treated as censored data. For catchments with frost during the winter season, summer and winter droughts have to be analysed separately.

1. Introduction

Drought is a major natural hazard having severe consequences in regions all over the world. In Europe the drought of 2003 affected 19 countries, and the total costs were estimated to exceed 11.6 billion Euro (EurAqua, 2004). Currently (summer 2005), another severe drought is striking Portugal, Spain, and parts of France and Italy (WMO, 2005). In 2003 many different sectors were affected, such as agriculture, forestry, water supply, energy and transport (navigation). The range of drought impacts is related to drought occurring in different stages of the hydrological cycle and usually different types of droughts are distinguished. The origin is a *meteorological drought*, which is defined as a deficit in precipitation. A meteorological drought can develop into a *soil moisture drought*, which may reduce agricultural production and increase the probability of forest fires. It can further develop into a *hydrological drought* defined as a deficit in surface water and groundwater, e.g. reducing water supply for drinking water, irrigation, industrial needs and hydropower production, causing death of fish and hampering navigation.

Drought is in this study defined as "a sustained and regionally extensive occurrence of below average natural water availability" (Tallaksen and van Lanen, 2004). This relative way of defining drought means that droughts can occur in any hydroclimatological region and at any time of the year. In response to the different impacts of drought in different regions a large number of quantitative drought characteristics have been developed. Recently published summaries can be found in e.g. Heim (2002), Hisdal et al. (2004), Smakhtin and Hughes (2004) and Hayes (2005). Drought characteristics are often referred to as drought indices or drought statistics when they are expressed as a single number. The choice of a suitable drought characteristic for a specific study depends on the hydroclimatology of the region, the type of drought considered and the vulnerability of society and nature in that region. As seen in Europe in 2003, however, a single drought event can cover a large region, spanning over different climate zones and affecting various human activities. Thus some standardisation of drought characteristics is preferable, in particular for the development of regional monitoring and forecasting systems which are important measures to mitigate the impacts of drought. Furthermore, the standardisation of drought characteristics will enhance comparative studies and assist the interpretation of drought. It is still advisable to describe the different kinds of drought (meteorological, soil moisture and hydrological drought) by separate drought characteristics, since they do not necessarily occur simultaneously nor exhibit the same severity. Keyantash and Dracup (2002) evaluate the most commonly used drought indices for the different types of drought. Most of these indices are adapted to data with a monthly or longer time resolution. In general, it can be expected that more detailed information can be obtained from a drought characteristic operating on shorter time resolutions, and in this study the focus is on streamflow drought characteristics derived from time series of a daily time resolution.

Generally, two main approaches of deriving streamflow drought characteristics can be distinguished (Hisdal et al., 2004). One is to analyse *low flow characteristics* such as a time series of the annual minimum *n*-day discharge, the mean annual minimum *n*-day discharge or a percentile from the flow duration curve (FDC). These characteristics describe the low flow part of the regime and characterise droughts only according to their magnitude expressed through the discharge (Tallaksen et al., 1997). The development in time of a drought event is not considered. A more detailed discussion of low flow characteristics is given by Fleig (2004). In the second approach, discharge series are viewed as a time dependent process, and the task is to identify the complete period of a drought event, from its first day to the last. In this way a series of drought events can be derived from the discharge series and droughts can be described and quantified by a number of different properties, so called *deficit characteristics*. Deficit characteristics such as drought duration or deficit volume are commonly derived by the threshold level method.

In drought studies design events are used for the construction of water reservoirs, which are one of the most important measures to cope with drought. Hydrological design often requires extrapolation beyond the range of observations and can be determined based on an extreme value analysis. A review of drought frequency analysis for a single site is given in Tallaksen (2000). Two common approaches to select extreme events from a time series are the block maxima (BM) and partial duration series (PDS) approach. In case of BM often the annual maxima is chosen. However, Engeland et al. (2004) found that a block size of at least two years was required for drought deficit volumes to avoid model bias. They therefore recommended the use of PDS as this reduces the standard errors in the design event estimates.

This study analyses streamflow drought characteristics for a wide range of flow regimes using the threshold level method. Its application to daily time series requires an additional pooling procedure to combine mutually dependent droughts. In order to allow some standardisation of streamflow drought characteristics the applicability of three pooling procedures: 1) the inter event criterion (IT-method), 2) the moving-average filter of *n* days (MA-procedure) and 3) the sequent peak algorithm (SPA) is evaluated for streams in different climate zones and with different hydrological regimes. The evaluation is based on the derivation of drought characteristics for a global data set of 16 daily discharge series, and the procedures are in particular evaluated for their applicability for perennial and intermittent streams and for comparison between different types of streams. Data requirements and limitations are also commented on. Finally, a frequency analysis of PDS of drought deficit characteristics is conducted, focusing on the choice of extreme value distribution.

The paper starts with presenting the Global Data Set used for the evaluation of the streamflow drought characteristics. It is followed by a detailed description of the threshold level method and the different pooling procedures, including data considerations and requirements. The application to the Global Data Set and the evaluation of the pooling procedure are then discussed prior to presenting the results of the frequency analysis of deficit characteristics. Finally, the main conclusions are summarised.

2. The Global Data Set

A global data set of 16 daily discharge series from around the world is used as a basis for the study (Fig. 1). The data set was assembled by the ASTHyDA project (ASTHyDA, 2005) in order to demonstrate the global variability of hydrological regimes. As such, it includes streams from most of the major climate zones as well as catchments of the same climate zone, but with different catchment characteristics (Rees et al., 2004). The catchment and discharge characteristics of the 16 streams are summarised in Table 1. The catchments are grouped according to their climate zones following the Köppen climate classification (Köppen, 1930). In this study streams are classified as perennial, when a stream is continuously flowing, intermittent, when parts of a stream fall dry during dryer times, or ephemeral, where precipitation is rare and water flows only directly after rainfall. Streams experiencing a frost season are additionally labelled "summer", since only droughts of the frost free season are considered. The hydrological regimes of the 16 stations are presented in Fig. 2.

The warm and humid *tropical* climate is represented by Honokuhau Stream on Hawaii, which has a flashy streamflow behaviour due to the strong and frequent convective rainfall events. The *dry* climate encompasses the *dry desert* climate, represented by the ephemeral river Dawib in Namibia, and the *dry steppe* climate, represented by the perennial Pecos River in New Mexico, USA. Here potential annual evaporation exceeds precipitation. The *temperate* climate is characterized by a high seasonal variation in temperature and in some regions also in precipitation. It is therefore further classified by the timing of the dry season. The *temperate winter dry* climate is represented by Elands River in South Africa, which has an average annual precipitation (AAR) of 500 mm and may run dry for shorter periods, and Bagmati River in Nepal, which experiences a monsoon climate and never runs dry. The fast responding river Sabar in Spain with long zero-flow periods and the river Arroyo Seco in California, USA, experience a *temperate summer dry* climate. In the catchment of Arroyo Seco precipitation shows high inter-annual variability, and the river may run dry for several months in one year and not at all in another. Belonging to the climate zone of a *temperate climate without dry season*, the three rivers Ray, Lambourn and Lindenborg are exposed to similar climate conditions (AAR 660–800 mm) but different hydrogeological characteristics. The catchment of Ray in the UK has impermeable soils and a flashy streamflow behaviour with frequent zero-flow periods. The river Lambourn, also in the UK, has a high base flow contribution and a delayed low flow period from August till November. The river Lindenborg in Denmark shows a mixed flow regime. Also the two rivers from New Zealand, Ngaruroro and Hurunui, experience a temperate climate without a dry season (AAR ∼2000 mm). Ngaruroro has a mixed response, but the baseflow contribution is lower than for Lindenborg. The catchment of Hurunui is partly snow covered during winter, but no pronounced snowmelt flood can be identified. Within the *cold* climate the length of the freezing period varies. When it is sufficiently long, low flows may also occur in winter as for the rivers Lågen in Norway and Inva in Russia. The catchment of Inva is located in a low lying area, which implies that the snowmelt flood is more distinct than for Lågen, whose catchment has an altitude range of 1500 m. The catchment of Ostri in Norway experiences a mixed cold and *polar* climate, and following the snowmelt flood melting water from glaciers contributes considerably to its summer flow. As an example of a large catchment covering two climate regions the river Rhine is included in the data set. At Lobith the catchment area is 160 800 km^2 and the catchment includes both temperate and cold climate regions.

All data series are quality controlled and periods of up to 15 days with incorrect values or missing data are filled in by interpolation. Years with more than 15 days of missing values are disregarded and the numbers of years with complete records are given in Table 1. The hydrological year is defined to start in the high flow season. For the only ephemeral river in the dataset, Dawib, only four consecutive years with a complete record existed. Therefore only a qualitative evaluation of the threshold level method can be provided for this type of river.

3. Threshold level method

The threshold level method originates from the theory of runs introduced by Yevjevich (1967), who originally defined droughts as periods during which the water supply does not meet the current water demand. Both the water supply, $S(t)$, as well as the water demand, $D(t)$, were expressed as time series, and a drought event was defined as an uninterrupted sequence of negative values in the supply-minus-demand series, $Y(t)=S(t)-D(t)$. Later, Yevjevich (1983) simplified the concept by applying a constant demand. The demand is represented by a threshold level, Q_z, and droughts are defined as periods during which the discharge is below the threshold level. Common deficit characteristics are the start of the drought, t_i, drought duration, d_i, deficit volume or severity, v_i, and the minimum flow occurring during the drought event, $Q_{\min,i}$, as illustrated in Fig. 3.

Since drought is defined as a period with below normal discharge, the threshold level should represent the boundary to "normal" conditions. Frequently a percentile of the daily flow duration curve (FDC) is applied, e.g. the 90-percentile flow (Q_{90}), which is the flow that is exceeded 90 percent of the time. Based on the FDC suitable threshold levels can be selected both for perennial streams with and without a frost season, as well as for intermittent streams. For perennial streams threshold levels in the range Q_{70} to Q_{95} are frequently applied. For intermittent streams lower exceedance percentiles have to be chosen, depending on the percentage of zero flow. Ephemeral streams are discussed in Sect. 3.3.

Originally, the threshold level method was developed for discharge series with a time resolution of one month or longer, but it has also been applied to daily discharge series, e.g. Zelenhasić and Salvai (1987) and Tallaksen et al. (1997). With a daily time resolution two problems have to be considered: the occurrence of minor droughts and mutually dependent droughts (Fig. 4). *Minor droughts* are events of short duration and small deficit volume. A high number of minor droughts in the sample may disturb an extreme value analysis and the number of minor droughts should thus be reduced. *Mu-*

tually dependent drought events can occur during a prolonged period of low discharge when excess periods with discharge above the threshold level divide the period of low discharge into several drought events. When the excess periods are of short duration, τ_i, and small excess volume, s_i, one would generally consider the period of low discharge to be one long drought event. The split drought events are called "mutually dependent droughts". They can be combined into larger events by so called *pooling procedures*, of which three are described in details in the next section.

3.1. Mutually dependent droughts

The *inter event time method* (IT-method), introduced by Zelenhasić and Salvai (1987), pools drought events based on an inter event time criterion (IT-criterion). Two mutually dependent droughts are pooled if they occur less than a predefined number of days, t_c, apart, i.e. $\tau_i \leq t_c$. The duration of the pooled drought event, the full drought duration, $d_{\text{pool f}}$, is defined to last from the first day of the first pooled event to the last day of the last pooled event, including the excess periods:

$$d_{\text{pool f}} = d_i + d_{i+1} + \tau_i \quad (1)$$

where d_i is the duration of event i. Furthermore, the pooled drought duration without excess periods, the real drought duration ($d_{\text{pool r}}$), can be of interest. The total pooled deficit volume, v_{pool}, is defined as the sum of the deficit volumes, v_i, of the pooled drought events:

$$v_{\text{pool}} = v_i + v_{i+1} \quad (2)$$

For studies focusing on e.g. reservoir management, a more consistent definition would be to subtract the inter event excess volume, s_i, from the sum of the deficit volumes.

In the *moving-average procedure* (MA-procedure; Tallaksen et al., 1997) a MA(*n*-day)-filter with an *n*-day averaging interval is employed that smoothens the discharge series, and as a result short excess periods are filtered out and mutually dependent droughts are pooled (Fig. 4). In this way both the time period between two drought events as well as the magnitude of the discharge values below and above the threshold level control the pooling of events. The original discharge series is modified by the smoothing such that the pooled event often starts (ends) a few days after (before) the first (last) day with discharge below the threshold level. The excess volume is automatically subtracted from the total deficit volume of the pooled event. Since the daily values are calculated as an *n*-day average, there is a possibility of introducing dependency between drought events if one event occurs less than *n* days after the preceding one without being pooled to it (Hisdal et al., 2004).

The *sequent peak algorithm* (SPA; Vogel and Stedinger, 1987) was developed for the design of water reservoirs. It derives the largest deficit volume of a discharge series with respect to a threshold level, Q_z. In this study it is used as a pooling procedure. A time series of the deficit volume $w(t)$ is derived by summing up the daily deficits between the discharge at time t, $Q(t)$, and the threshold level and subtracting the excess volumes until $w(t)$ returns to zero (Fig. 5). When $w(t)$ equals zero, excess volumes are not subtracted, thus, $w(t)$ never turns negative:

$$w(t) = \begin{cases} w(t-1) + Q_z - Q(t) & \text{if} \quad w(t-1) + Q_z - Q(t) > 0 \\ 0 & \text{if} \quad w(t-1) + Q_z - Q(t) \leq 0 \end{cases} \tag{3}$$

The largest deficit volume, $w_{\max}$, is then selected for each uninterrupted period of deficit, i.e. $w(t)>0$. A pooled drought event is considered to start on the first day with $w(t)>0$ and to end when $w_{\max,i}$ is reached. The total pooled deficit volume of the event is $w_{\max,i}$. Drought events are thus pooled until $w_{\max,i}$ is reached. In the time period following $w_{\max,i}$ and until the deficit volume, $w(t)$, is back to zero, the stream is not considered to be in a drought situation, since the average discharge of this period exceeds the threshold level.

3.2. Minor droughts

When the MA-procedure is applied as a pooling procedure, minor droughts are automatically filtered out. When the IT-method or SPA is applied minor droughts have to be excluded in an additional step. Here they are excluded when their deficit volume is smaller than a certain percentage α of the maximum observed deficit volume ($v_i \leq \alpha \times v_{\max}$), or when the real drought duration is shorter than a given minimum value, $d_{\min}$, ($d_{\text{pool r}} \leq d_{\min}$).

3.3. Characteristics of streamflow regimes

The application of the threshold level method to perennial streams is normally straightforward, with the exception of streams experiencing pronounced seasonal differences as discussed below. Intermittent streams dry out, implying that the deficit volumes do not increase with increasing drought duration in the same way as during flow periods. The deficit volumes of intermittent streams can thus not be interpreted in the same way as those of perennial streams, and in case of a frequency analysis the deficit volumes of zero-flow periods should be treated as censored data. For ephemeral streams with rare and short flow events the severity of a drought is reflected by the duration of zero-flow periods and the total flow volume rather than by deficit periods during a flow event. The application of the threshold level method for daily data is therefore not appropriate. Alternative drought characteristics are the duration of zero-flow periods, total volume of flow events or total annual discharge, as well as characteristics derived from groundwater or reservoir data.

Streamflow droughts can be of different origin due to seasonality in the hydroclimatological processes, for instance in regions experiencing a wet and a dry season or a warm and a cold season. In regions with a cold winter season two different types of streamflow droughts have to be distinguished: *summer droughts* caused by low precipitation and often accompanied by high evapotranspiration losses, and *winter droughts* occurring when temperature is below the freezing point and water in the catchment is stored as snow and ice. If droughts are of different origin, it has to be decided whether deficit characteristics ought to be calculated for each type separately, e.g. in case of a frequency analysis, or whether it is acceptable to derive a mixed series of drought events. If the droughts are to be separated, the seasons and the procedure to identify seasonal droughts have to be specified. In addition, it is necessary to decide whether the threshold level should be based on the whole year or on seasonal data.

Seasonal calculations are recommended for streams with a cold winter season, since they often experience two annual low flow periods caused by different processes. Streams with one wet and one dry season usually experience only one low flow period, and in case of an all-year study only dry-season droughts are derived. However, in order to study wet-season droughts, separate seasonal calculations are necessary as suggested by Tate and Freeman (2000) for wet-season droughts in Southern Africa.

For frost influenced catchments Hisdal et al. (2001) specified fixed seasons and defined the summer as the period with mean monthly temperature above the freezing point. In case of an annual snow-melt flood, the start of the summer season was defined to be at the end of the flood period to avoid that very high flow values influence the seasonal threshold level. The use of fixed seasons does not account for the fact that the frost period actually varies from year to year and as a result drought events might be cut off or incorrectly classified into a summer or winter drought. However, defining the seasons for each year separately would require daily temperature data. Alternatively, droughts can be derived from the complete time series and classified as e.g. summer droughts if their major part, in terms of deficit or duration, belongs to a predefined summer season. This means that neither late-ending summer droughts are cut off, nor are parts of early winter droughts included in the sample of summer droughts. The events should in this case be classified prior to pooling. However, in catchments with a long winter season, as for the two Norwegian catchments Lågen and Ostri, it can happen that a severe summer drought develops into an even longer winter drought and is thus misclassified as a winter drought. For catchments with a short winter season, as for Pecos River in New Mexico, a whole winter season might be included in a drought classified as summer drought. There are no simple solutions to these difficulties encountered when classifying summer droughts that continue into the winter season. Should they be considered to end at some fixed date (censored data sample) or continue into the winter season (non-homogeneous data sample)?

The use of a censored data sample has been suggested by Tate and Freeman (2000) for wet-season droughts and could also be tested for summer droughts.

A similar problem concerns catchments that cover a large altitude range or have a large areal extension in which case the seasonal behaviour can vary within the catchment as for the river Rhine at Lobith, the Netherlands. On average the lower parts of the catchment experience continuous frost periods only for a few days, while the frost periods in the mountainous areas last for several months. In such cases the specification of a summer season must depend on the hydrological regime at the site of interest, baring in mind the complexity of the catchment area in the evaluation of the results.

If seasonality is present it is recommended to derive separate threshold levels for each season, since a FDC of the summer period may differ considerably from the FDC of the complete data record. For example for the river Lågen, Norway, the fixed summer season lasts from 15 June until 30 September. The $Q_{90\text{Year}}$=2.97 m^3/s is approximately five times smaller than $Q_{90\text{Summer}}$, and even lower than the observed lowest summer discharge of 6.30 m^3/s. Thus, with $Q_{90\text{Year}}$ as threshold level no summer droughts would be selected. In this study the following stepwise procedure has been adopted for seasonal calculations:

1. specification of the start and end date for the season of interest;
2. determination of threshold level based on seasonal data;
3. selection of drought events for the whole year;
4. classification of each drought event according to which season its longest part belongs to;
5. pooling of the seasonal drought events.

4. Evaluation of pooling procedures

The threshold level method combined with the pooling procedures outlined in the previous section is applied to the perennial and intermittent streams from the Global Data Set. The results are summarised in the following by describing the determination of the pooling parameters, presenting selected applications, which illustrate advantages and limitations of the different procedures, and comparing the derived deficit characteristics. The determination of the pooling parameters is based on a selection of streams from the Global Data Set representing the various streamflow regimes.

4.1. The IT-method

For the IT-method the parameter value, t_c, has to be determined. Tallaksen et al. (1997) recommended t_c=5 days, based on the relationship between t_c and the mean deficit characteristics for two perennial streams in Denmark. However, they used an additional inter event volume criterion (IV-criterion) for pooling. Zelenhasić and Salvai (1987) recommended t_c=6 days based on their experience with two perennial rivers in former Yugoslavia and this value has also been applied for intermittent streams (e.g. Woo and Tarhule, 1994). Here a sensitivity analysis of t_c is performed to judge whether these recommendations also apply to streams from other flow regimes. In case of the perennial streams (Lindenborg, Ngaruroro, Bagmati River and Honokohau Stream) Q_{90} is applied as threshold level. For the intermittent streams the threshold is selected depending on the occurrence of zero flows, Q_{70} for Arroyo Seco, Q_{50} for Ray and Q_{20} for Sabar. The mean deficit characteristics of the annual maximum series (AMS) of non-zero values are analysed, rather than of the PDS, to reduce the influence of the number of minor droughts and the number of pooled events. The mean values of deficit volume and real drought duration are calculated for t_c=0, 2, 5, 7, 10, 15, 20 and 30 days, where t_c=0 days represents the drought series without pooling. The mean deficit volume and duration are standardised by the mean of t_c=0 day. The relationships between t_c and the deficit characteristics are shown in Fig. 6.

The sensitivity curves generally start to level out around t_c=5 days and for most streams the drought characteristics do not change substantially after t_c equals 10 to 15 days implying that a maximum of pooling is obtained. For Honokohau Stream and Sabar, however, the standardised mean deficit characteristics continue to increase. For Honokohau Stream this is due to the flashy discharge behaviour and the frequent occurrence of drought events. Sabar, on the other hand, is an intermittent stream with a distinct dry season. Its standardised mean deficit characteristics increase due to an increasing number of multi-year droughts with increasing t_c. This is mainly a result of the high threshold level chosen for Sabar (Q_{20}). Contrarily, for the other intermittent stream with a distinct dry season, Arroyo Seco, the choice of t_c is of little importance as the threshold level in this case is sufficiently low (Q_{70}) to avoid wet-season and multi-year droughts. The choice of t_c is in this case not important, since the dry season is usually not split into several events. Hence, in case of a distinct dry season, pooling generally has no effect as long as the threshold level is selected sufficiently low.

The sensitivity analysis suggests that the value recommended by Tallaksen et al. (1997), t_c=5 days, can be applied for perennial as well as intermittent streams with the exception of very flashy streams. The applicability of the IT-method for flashy streams is further discussed in Sect. 4.4.

4.2. The MA-procedure

For the MA-procedure Tallaksen et al. (1997) suggested an averaging interval of n=10 days for perennial rivers in Denmark. This study included the river Lindenborg. It is here tested whether this value can also be recommended for flashy (Honokohau Stream) and intermittent streams (Ray and Arroyo Seco). The mean deficit volume and mean real drought duration of the AMS of non-zero values are calculated and standardised by the mean of the non-pooled AMS. Due to the smoothing of the discharge series using a MA(n-day)-filter, the mean deficit characteristics are not strictly increasing with increasing n. An appropriate value for n can be selected when the mean characteristics reach a maximum or when they level out. The averaging interval n should be chosen as small as possible, since a MA(n-day)-filter modifies the discharge series. The MA-procedure has two effects which can both result in an increase of the mean deficit characteristics: pooling of events and elimination of minor droughts. The latter only has an effect if it results in an increase in zero-drought years.

AMS of drought events are obtained for n=5, 10, 15 and 20 days with a threshold level of Q_{90} for the perennial streams and Q_{70} and Q_{50} for Arroyo Seco and Ray, respectively. The relationships between n and the standardised mean deficit characteristics are displayed in Fig. 7. For Arroyo Seco, Lindenborg and Ray the curves flatten at n=5, 7 and 10 days, without being influenced by an increase in zero-drought years. These values for n can thus be considered optimal to select drought events. For Honokohau Stream the mean deficit characteristics reach a maximum at n=15 days and a local maximum at n=7 days. The maximum at 15 days is mainly caused by an increase in zero-drought years, whereas the maximum at 7 days corresponds to the maximum deficit characteristics. A moving-average interval of n=7 days is therefore considered optimal for Honokohau Stream. In general it is concluded that an averaging interval of the order of 7 days is appropriate for these streams.

4.3. The SPA

An advantage of the SPA is that it requires no parameters in addition to the threshold level. However, the application of the SPA as pooling procedure revealed a major problem related to the original purpose of deriving the largest observed deficit volume. For example, within the 35 year long data record of Lindenborg the five most severe drought events occurred between 1974 and 1978 using Q_{90} as threshold level. The fourth most severe event occurred in 1977 (Fig. 8, upper graph). A threshold of Q_{80} implies that the events from 1975, 1976 and 1977 are pooled into one multi-year drought and the maximum deficit volume is reached in October 1976 (Fig. 8, lower graph). The drought is thus considered to end in October 1976 and the year 1977 is considered to be drought-free. Drought events that occur shortly after a major event get pooled to this event, but are not accounted for in any way, neither in the deficit volume nor the duration of the major event. This applies also to within-year droughts. Hence, the SPA is not suited as pooling procedure for the selection of a PDS. For an AMS its use should be limited to very low threshold levels to avoid that events following a major drought are not recognized.

4.4. Comparison of the pooling procedures

The degree of pooling of the three procedures is compared, employing n=7 days for the MA-procedure and t_c=5 days for the IT-method. The chosen threshold levels are the same as for the determination of pooling parameters. The deficit characteristics of the 10 largest events are compared, since the criteria to exclude minor droughts differ between the three procedures. It is found that for all types of streams the MA-procedure derives more but somewhat smaller events. This lower degree of pooling is mostly due to the choice of averaging interval. Based on an additional comparison for Lindenborg it is suggested that n=10 days gives the most similar results as compared to the 5-day-IT-method and the SPA. The IT-method and SPA pool drought events in a comparable manner for low threshold levels, not showing any streamflow-type specific differences. When higher threshold levels are chosen, the degree of pooling is much higher with the SPA and the problems discussed above can occur. The largest differences in pooling are observed for fast responding catchments, such as Honokohau Stream and Ray. Honokohau Stream shows a particular flashy discharge behaviour due to the high frequency of rain events. For this stream the degree of pooling is much higher with the IT-method as compared to the MA-procedure and SPA as illustrated in Fig. 9. The shaded areas in Fig. 9 indicate the deficit volumes of a non-pooled drought series and the lines below show the drought periods as they are pooled by the 5-day IT-method (upper lines), MA(7-day)-filter (middle lines) and SPA (lower lines). The events selected by the MA-procedure or the SPA last much shorter compared to the events obtained by the IT-method. For example from mid August 1945 to mid September 1945 a series of seven minor drought events are pooled to a subsequent large drought with the IT-method. Thus considering the pooled event to start on 13 August as opposed to the start of the major drought more than one month later on 19 September. With the MA-procedure and SPA these minor droughts are not pooled, since pooling is also determined by the inter event excess volume. It is anticipated that thus the use of an additional IV-criterion would improve the IT-method.

It can be concluded that for the studied types of streams (perennial with and without cold winter and intermittent with and without dry season) the three tested pooling procedures can be applied with the following limitations:

- The IT-method is not recommended for flashy streams. An additional IV-criterion could possibly improve the method.
- The MA-procedure modifies the discharge series and thus deficit volume and duration. It might also introduce dependency between pooled drought events.
- As pooling procedure the SPA is only advisable for the study of AMS rather than PDS. It is also limited to very low threshold levels.

General recommendations for seasonal calculations are given in Sect. 3.3. For comparative studies the MA-procedure is considered the most flexible approach, keeping in mind the above mentioned limitations.

5. Frequency analysis

Partial duration series (PDS) of drought events are derived from time series of daily discharge using the threshold level method as outlined in the previous sections. The PDS model includes two stochastic model components, the number of extreme events occurring in a given time interval and the magnitude of the events (deficit volume or duration). The Generalized Pareto (GP) distribution can be shown to be the limit distribution of scaled excesses over a certain limit and is thus suited to model PDS of magnitudes (Tallaksen et al., 2004). When the number of extreme events in the PDS is assumed to follow the Poisson distribution and the magnitudes the GP distribution, the Generalized Extreme Value (GEV) results for the annual maximum series. Annual exceedance probabilities can be estimated from the PDS provided the average number of events per year larger than the limit is known. Following Zelenhasić and Salvai (1987) the distribution of the largest streamflow drought deficit in a given time interval, e.g. one year, $H(x)$, is derived based on the distribution function of the magnitudes of all events within the time interval, $F(x)$, combined with the distribution function of the number of droughts occurring in the time interval:

$$H(x) = \Pr(E=0) + \sum_{k=1}^{\infty} F^{k}(x)\Pr(E=k) \quad (4)$$

where $\Pr(E=k)$ is the probability that k events occur during the time interval (E is the number of events). It is assumed that the drought deficits (magnitudes) are independent, identically distributed (*iid*) random variables with mutually independent deficits and occurrences for all events. Only drought events lasting less than one year are included.

The program NIZOWKA (Jakubowski and Radczuk, 2004) is applied for the selection of droughts and the extreme value analysis. The magnitudes of the drought events comprising a PDS of drought deficit volume or duration are derived for two threshold levels, i.e. Q_{90} and Q_{70}. In general, the 5-day IT-method is used as pooling procedure, whereas the MA(7-day)-filter is applied for Honokohau Stream. Minor droughts are excluded when the deficit volume is smaller than a certain percentage, α=0.5%, of the maximum observed deficit volume, and the real drought duration is smaller than $d_{\min}$=3 days. This combination of α and $d_{\min}$ was found to be the best choice comparing the nine tested combinations with α=0, 0.5 or 1% and $d_{\min}$=1, 3 or 5 days. Higher values of α and $d_{\min}$ have the advantage of excluding a larger part of minor droughts, often implying less model bias and thus a better fit to the most extreme droughts. However, the number of drought events has to be sufficiently high to avoid large uncertainties in the estimated design event. The optimum number of events is found as a compromise between selecting extremes following an extreme value distribution and a sample size needed for sufficiently precise estimations.

NIZOWKA allows several probability distributions to be fitted to the series of deficit volume or deficit duration by the method of maximum likelihood. This encompasses the Poisson and Pascal distribution for the occurrence of the events and the Gamma, Weibull, Log-Normal, Johnson, Gumbel and Generalized Pareto distribution for the magnitudes of the PDS, $F(x)$. The model fits are tested by a χ^2-goodness-of-fit test (Haan, 1977). The test does not allow determination of the "best" or "true" distribution model (Stedinger et al., 1993), but gives an indication of which models perform reasonably well. The choice of the distribution for $\Pr(E=k)$ is observed to be of minor influence for $H(x)$, and the Poisson distribution is chosen. The fit of the obtained distribution functions for $H(x)$ is then visually compared with the observed AMS. In the visual comparison the overall fit to the complete AMS of observations is considered as well as the fit in the extreme range. The extreme range is considered to consist of the three to five largest observed events, depending on the length of the series. The models for $H(x)$ are in the following labelled according to the models used for $F(x)$ and $\Pr(E=k)$, e.g. a combined GP/Poisson model which actually corresponds to a GEV model for the AMS.

The described procedure is illustrated for deficit volumes for the river Lindenborg in which case the GP, Log-Normal, Weibull and Gamma distribution models all can be accepted at a significance level of 0.05 for the PDS. The highest significance level, ρ, in the χ^2-goodness-of-fit test is obtained for the Log-Normal model (ρ=0.71) and the second highest for the GP model (ρ=0.50). The visual comparison (Fig. 10) of the distributions for $H(x)$ shows that the GP/Poisson model gives the best fit to the extreme range, where the deviations between the different models is largest. Using the GP/Poisson model the relative deficit volume, which is the deficit volume of an event relative to the daily mean discharge volume, of the drought event with a 50-year return period is estimated to 22.2. The estimates based on the other three models vary between 11.8 and 14.9, thus being 33–47% lower than the GP/Poisson estimate. This demonstrates the high uncertainty in the estimate of return levels related to the choice of distribution.

In total 43 estimations are successfully derived for the whole Global Data Set. This includes estimations for deficit volume, v, and duration, d, of 10 perennial streams for two different threshold levels and duration of three intermittent streams. Duration is defined as the full drought duration (Eq. 1). No estimations are done for deficit volumes of intermittent streams. In Table 2 the performance of the combined GP/Poisson model is compared to other models. Only models that achieved a significance level larger than 0.02 in the χ^2-goodness-of-fit test for $F(x)$ are considered. In 57% of the cases, the GP/Poisson model fits best in the range of the most extreme events or for the whole range of drought events. In an additional 21.5% of the cases the GP/Poisson model performs equally well as the other models. Only in 21.5% of the cases other models perform better. This is in agreement with the extreme value theory, which states that excesses over a certain limit are Generalized Pareto (GP) distributed. The GP/Poisson model can thus be recommended for AMS of deficit characteristics in perennial and intermittent streams.

6. Conclusions

Droughts are natural hazards which can cover large regions and last for long periods of time. This implies that robust drought characteristics applicable in regions with different hydroclimatology and hydrogeology are needed. In this study the threshold level method for the derivation of streamflow drought characteristics is evaluated for a daily time resolution along with three pooling procedures. The pooling procedures are designed in order to overcome the problems of minor and mutually dependent droughts. The procedures are judged based on their applicability to different types of streams and for comparability between streams. The threshold level method proved to be a suitable method for perennial and intermittent streams and useable both for all-year as well as seasonal series. For ephemeral streams, other drought characteristics, like the duration of the zero-flow periods, are considered to provide more relevant information of the drought condition in the catchment.

For regional applications, which include different types of streams, both the IT-method and the MA-procedure can be used. The applicability of the SPA should, however, be limited to very low threshold levels to ensure that also events occurring shortly are after major events are recognized. It is further recommended that the IT-method is extended to include both a time and volume based criterion as also suggested by Tallaksen et al. (1997). For flashy streams with frequent crossing of the threshold level, the IT-method tends to pool too many events. In these fast responding catchments it is necessary to consider also the excess volume, which can be considerable also for short excess periods. The MA-procedure is applicable to both fast and slowly responding streams and its parameter, the averaging interval, can easily be optimised for each stream. A drawback is that it modifies the discharge series and may thus introduce dependency between the drought events.

A remaining challenge is how to define seasonal drought events, in particular severe summer droughts that continue as long winter droughts. A frequency analysis of seasonal droughts requires that the events are *iid*, which in this case implies a choice between working with censored data, i.e. summer droughts are cut off at the start of the winter season, or non-homogeneous data when combined summer and winter droughts are considered to belong to either the summer or winter season by a predefined rule, e.g. the longest duration. It remains to be tested what the best model is for the various flow regimes in cold regions.

Regional drought studies require a consistent set of drought characteristics that can be applied across the region. Deficit characteristics derived by the threshold level method proved to give comparable results for different kinds of streams. This is an advantage when estimates of design events are derived across a larger, often heterogeneous region. It was further found that the Generalized Pareto model is a good choice for the distribution of the magnitudes of drought events (PDS of deficit volume and duration) for most streams, thus supporting the theoretical base of extreme value modelling. There are large uncertainties related to fitting distributions based on observations only, in particular in the tail of the distributions. It is therefore recommended to let the choice of distribution function be guided by extreme value theory as this will likely give better predictions of the most extreme events.

A regional monitoring system commonly adapts to simple measures like relating the current streamflow to a value from the flow duration curve. A drought forecasting system on the other hand, depends on our ability to link large scale climate drivers to the frequency and occurrence of drought at the land surface. This requires that both the temporal and spatial development of drought causing processes in the climate and terrestrial system can be compared. For streamflow droughts the threshold level method is found to be a flexible approach for a wide range of flow regimes, capturing both the duration and the severity of a drought event. The possible link between drought and regional scale weather patterns will be investigated in a further study, including deficit characteristics as presented here.

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Table 1. Catchment and discharge characteristics of the streams of the Global Data Set (with AAR: average annual precipitation; q: specific discharge; c_{zero}: percentage of zero-flow; CV: coefficient of variation).

Stream, Site	Country	Köppen Climate Zone	Streamflow type	Area	Station Altitude (km^2)	Maximum Altitude (m a.m.s.l.)	AAR (mm) (m a.m.s.l.)	q (l/(s.km^2))	c_{zero} (%)	CV	Number of used years
Honokohau Stream, Honokohau	Hawaii, USA	Af: Tropical	perennial	11	256	ca. 1765[1]		98.36	0.0	1.23	53
Dawib, Dawib	Namibia	Bw: Dry – desert	ephemeral	560	>200[1]	<2000[1]		0.02	98.2	14.17	4
Pecos River, Pecos	New Mexico, USA	BS: Dry – steppe	perennial, seasonal	490	2287	ca. 3993[1]	474–610	5.92 (7.34)[6]		1.30	68
Elands River, Elands River Drift	South Africa	Cw: Temperate – winter dry	intermittent	690	1000–1500[1]	poss. >3000[1]	500	3.53	3.0	2.44	13
Bagmati River, Sundarijal	Nepal	Cw: Temperate – winter dry	perennial	17	1600			62.88		1.02	22
Sabar, Alfarnatejo	Spain	Cs: Temperate – summer dry	intermittent	39	ca. 900[2]	1671[1]		4.54	50.9	3.62	29
Arroyo Seco, Soledad	California, USA	Cs: Temperate – summer dry	intermittent	632	103		802–864	7.66	12.5	3.35	68
Ray, Grendon Underwood	United Kingdom	Cf: Temperate – no dry season	intermittent	19	66	187	660	5.11	26.4	2.76	26
Lambourn, Shaw	United Kingdom	Cf: Temperate – no dry season	perennial	234	76	261	805	7.25	0.0	0.48	36
Lindenborg, Lindenborg Bro	Denmark	Cf: Temperate – no dry season	perennial	214	5	113	741[3,4]	10.90	0.0	0.35	37
Ngaruroro, Kuripapango	New Zealand	Cf: Temperate – no dry season	perennial	370	500	1617	2000–2150[5]	46.97	0.0	1.06	34
Hurunui, Mandamus	New Zealand	Cf: Temperate – no dry season	perennial, summer	1060	300	1987	1919	49.79 (45.16)[6]	0.0	0.86[6]	40
Lågen, Rosten	Norway	Df: Cold – no dry season	perennial, summer	1755	737	2200	700	52.24 (31.26)[6]	0.0	0.83[6]	84
Inva, Kudymkar	Russia	Df: Cold – no dry season	perennial, summer	2050	0–100[1]	200–500[1]	700–800	6.06 (6.91)[6]	0.0	1.87[6]	56
Rhine, Lobith	The Netherlands	Df, Cf: Cold, Temperate	perennial, (summer)	160 800	10	4275	716	13.74 (13.00)[6]	0.0	0.51 (0.46)[6]	92
Ostri, Liavatn	Norway	Df, ET: Cold, Polar	perennial, summer	235	733	2088	1560	44.69 (98.39)[6]	0.0	0.61[6]	34

[1] from The Times (1994) [2] from SUR in English (2005) [3] from Ovesen et al. (2000) [4] average for the period 1971–1998 [5] Clausen, 2003 personal communication [6] summer

Table 2. Performance of the combined GP/Poisson model compared to the performance of other models.

Estimation	Number of stations with estimations	Number of stations for which			
		GP/Poisson shows best overall fit	GP/Poisson fits best to extreme events	GP/Poisson fits equally well as others	Other models fit better
$v: Q_z{=}Q_{90}$	10	4	3	3	0
$d: Q_z{=}Q_{90}$	8	1	4	1	2
$v: Q_z{=}Q_{70}$	11	6	1	1	3
$d: Q_z{=}Q_{70}$	13	4	1	4	4
Total	42	15	9	9	9

Fig. 1. Catchments of the Global Data Set (modified from Rees et al., 2004).

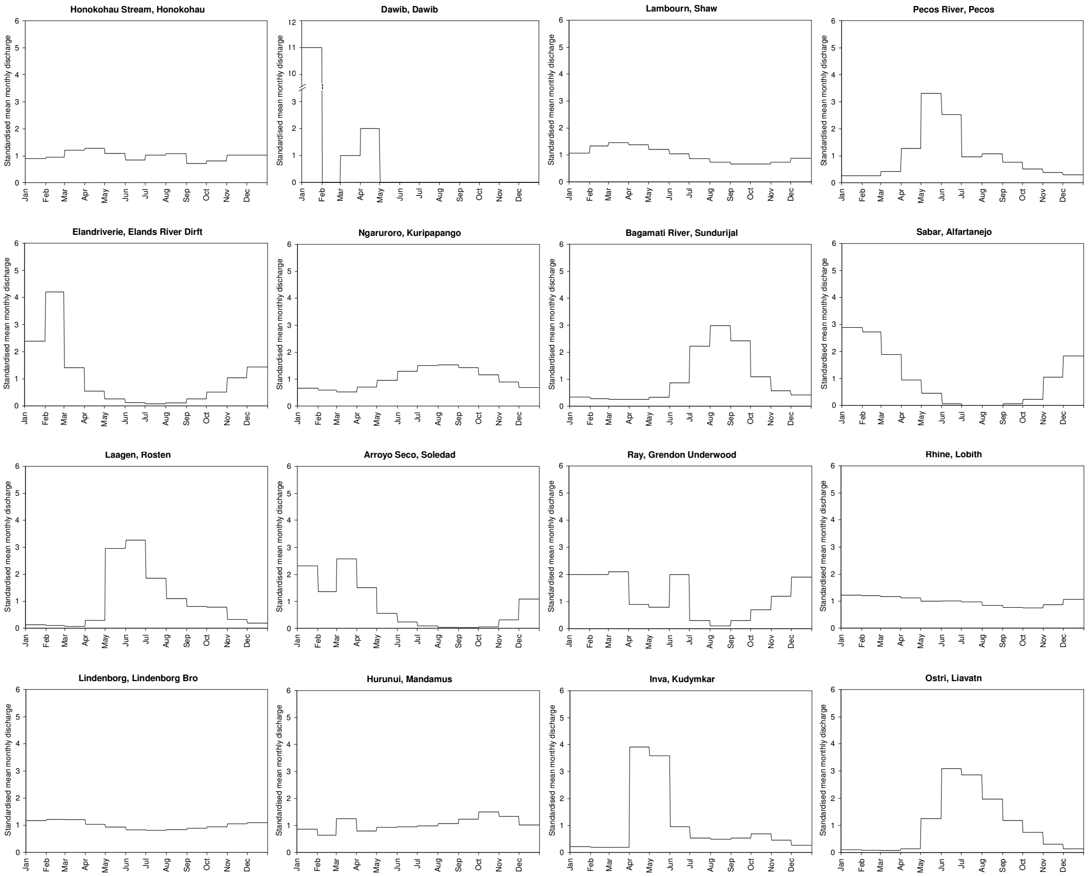

Fig. 2. Mean monthly discharges standardised by the mean discharge for the 16 stations of the Global Data Set.

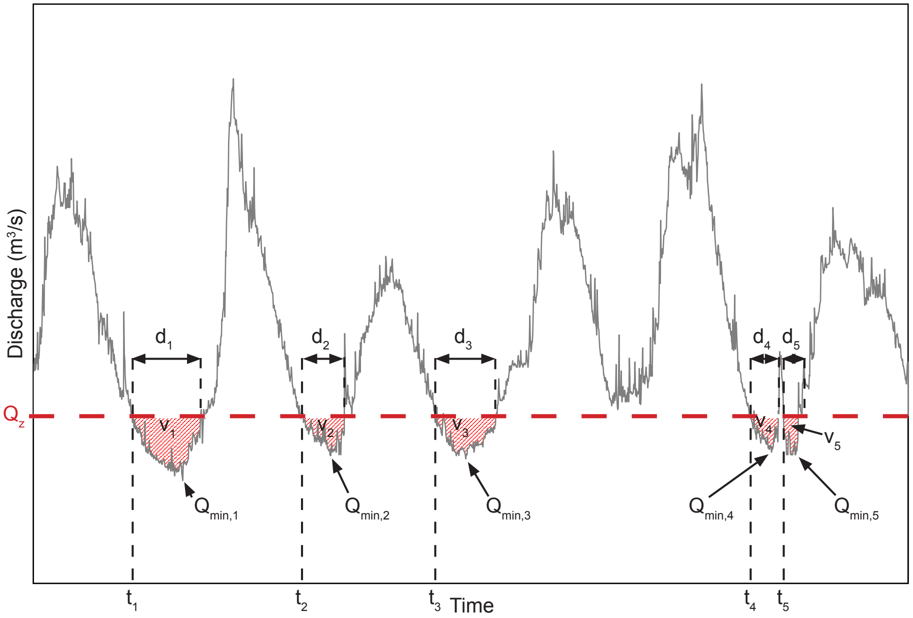

Fig. 3. Illustration of commonly used deficit characteristics as defined with the threshold level method: time of occurrence, t_i, duration, d_i, deficit volume or severity, v_i, and the minimum flow occurring during the drought event, $Q_{\min,i}$.

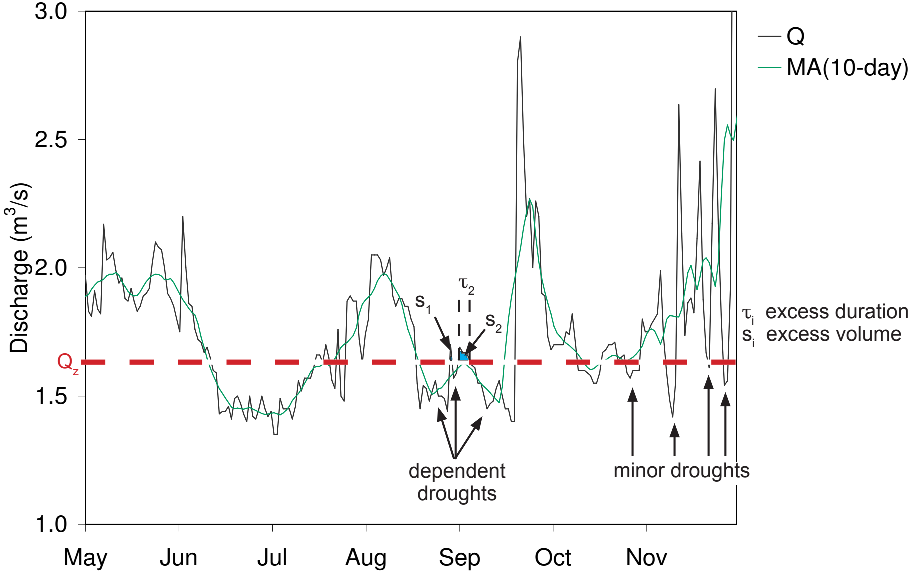

Fig. 4. Illustration of the pooling of mutually dependent droughts and the removal of minor droughts by an MA(10-day)-filter.

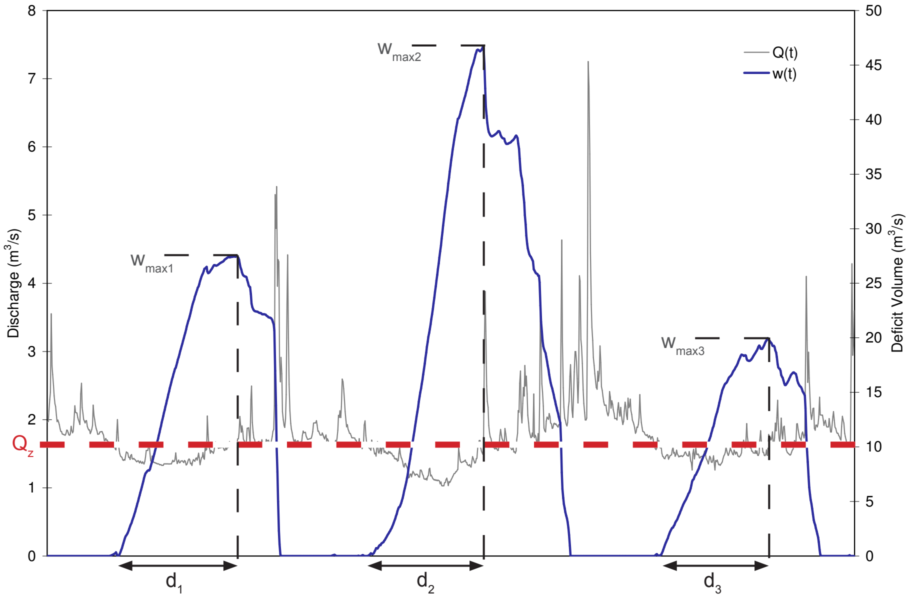

Fig. 5. Illustration of the derivation of the deficit characteristics duration, d_i, and deficit volume, $w_{\max,i}$, by the SPA.

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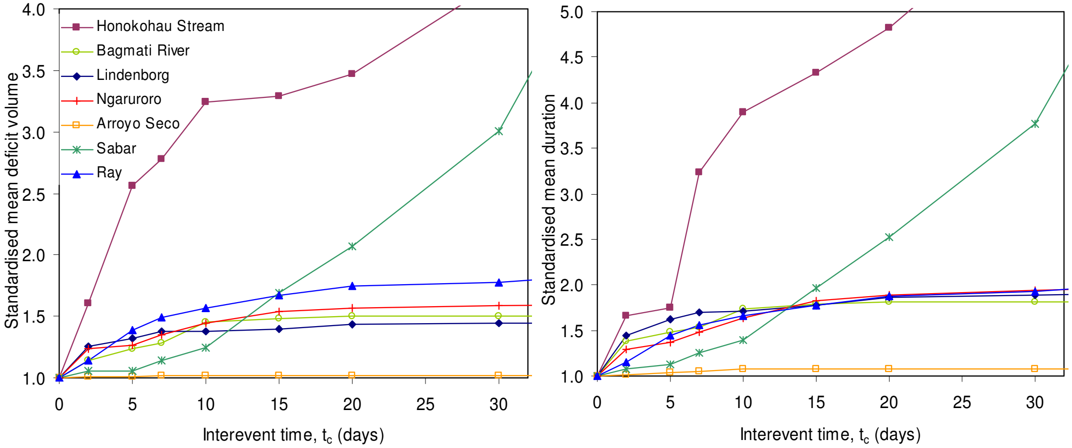

Fig. 6. Relationship between the inter event time and the standardised mean deficit volume (left) and the standardised mean duration (right).

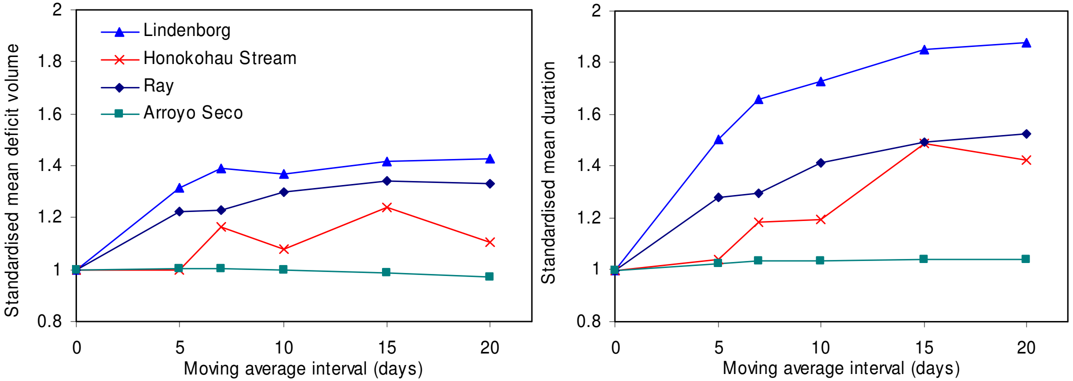

Fig. 7. Relationship between the moving-average interval and standardised mean deficit volume (left) and standardised mean duration (right) for Lindenborg, Honokohau Stream, Ray and Arroyo Seco.

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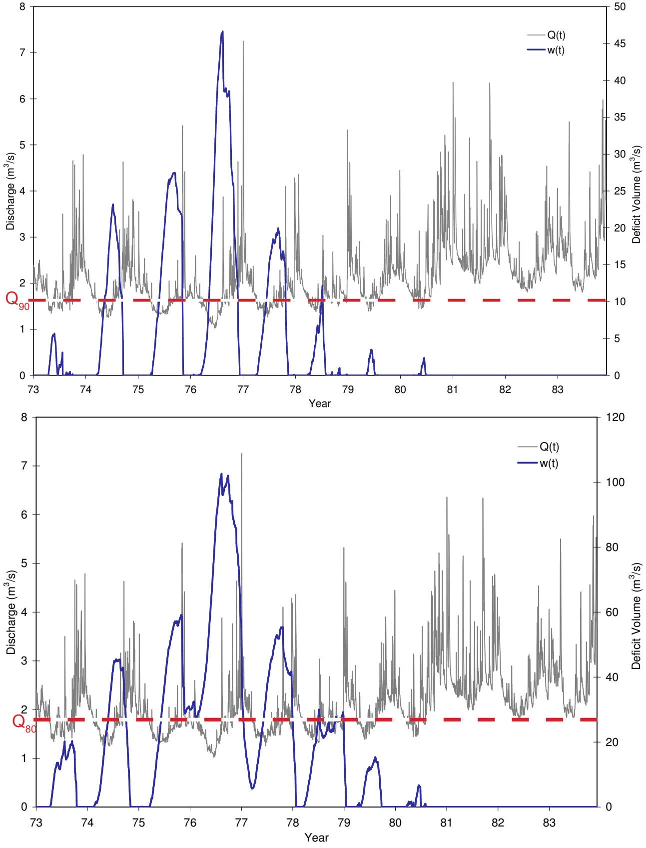

Fig. 8. The deficit volume, $w(t)$, in (m^3/s) derived by the SPA for the period 1973 to 1983 for the river Lindenborg, for two different threshold levels, Q_z. Upper: $Q_z=Q_{90}$. Lower: $Q_z=Q_{80}$.

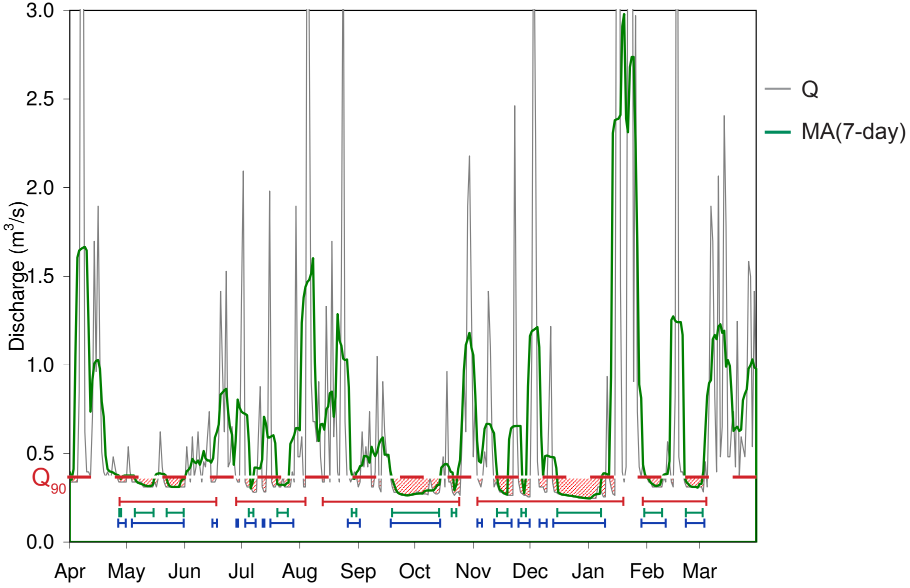

Fig. 9. Differences in pooling by the 5-day IT-method (upper lines), a MA(7-day)-filter (middle lines) and the SPA (upper lines) for Honokohau Stream for 1945. The non-pooled droughts are marked as shaded areas.

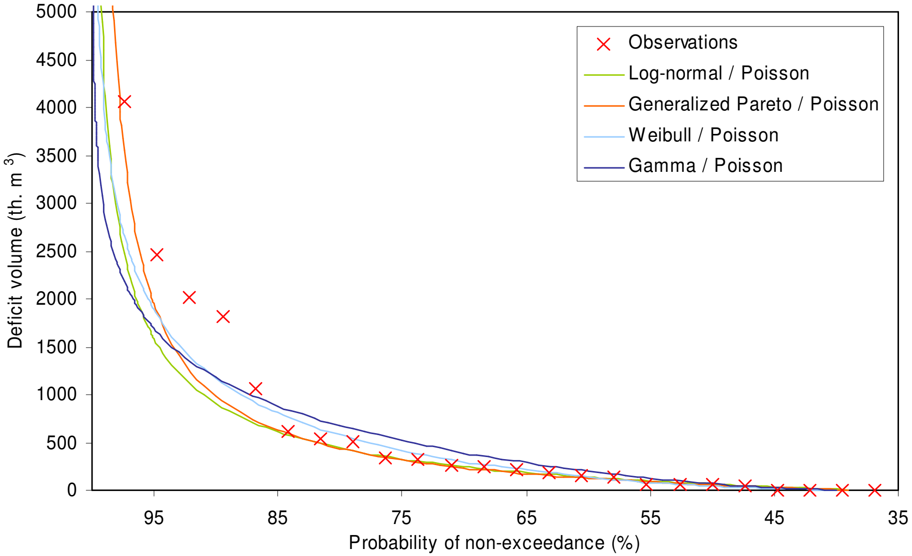

Fig. 10. Different distribution models for $H(x)$ compared to the AMS of observed deficit volumes for the river Lindenborg.