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Hydrological Drought – A comparative study using daily discharge series from around the world

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Ehrenwörtliche Erklärung:

Hiermit erkläre ich, dass die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Oslo, 15. März 2004 Anne Fleig

Preface

These last nine months while working on my *Diplomarbeit*, were a very enriching and of course, sometimes also exhausting time. That it was an exhausting time, I guess, is just the nature of any thesis, but that it also was an enriching time, was, because I could do this thesis in Oslo and work on an interesting hydrological topic. It was inspiring to work on a hydrological topic for a longer time and in more detail, making a first hand experience in hydrological research. I want to thank Dr. Lena Tallaksen, University of Oslo and Prof. Dr. Siegfried Demuth, Albert-Ludwigs-University Freiburg, who gave me the opportunity to work on this project and supervised my work. I also want to thank Dr. Hege Hisdal, my coordinator at the Norwegian Water and Energy Directorate (NVE). Thanks also to NVE, who gave me space and a computer to work.

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Abbreviations and Symbols

Abbreviations

AM(*n*-day)	Annual minimum *n*-day discharge
AMS	Annual maximum/minimum series
ASTHyDA	Analysis, Synthesis and Transfer of Knowledge and tools on Hydrological Droughts Assessment through a European network
BFI	Base Flow Index
EDA	Exploratory data analysis
FDC	Flow duration curve
FDC_S	Flow duration curve for the summer season
FDC_Y	Flow duration curve for the whole year
FRIEND	Flow Regimes from International Network Data
GP	Generalized Pareto
IC	Interevent time and volume criterion
iid	Identically and independently distributed
IT	Interevent time criterion
IV	Interevent volume criterion
MA	Moving average
MA(*n*-day)	Moving average with an averaging interval of *n* days
MAM(*n*-day)	Mean annual *n*-day minimum
PDS	Partial duration series
Pr	Probability
S	Summer
SPA	Sequent Peak Algorithm
Y	Year

Symbols

$1 - \alpha$		Confidence level
AAR	[mm]	Mean annual precipitation
$AM(n)$	[m^3/s]	Annual minimum n-day discharge
$AM(n)_T$	[m^3/s]	Estimated T-year annual minimum n-day discharge
$Area$	[km^2]	Catchment area
BFI		Base Flow Index
c_{zero}	[%]	Percentage of time with zero discharge
CVa		Coefficients of variation of annual data series
CVd		Coefficients of variation of daily data series
$D(t)$	[m^3/s]	Water demand series
d_i	[days]	Drought duration of event i
d_{min}	[days]	Minimal drought duration (criterion to exclude minor drought events)
d_{pool}	[days]	Pooled total drought duration
e_i		Drought event i
E_i		Empirical number of observations per class
$e(x)$		Event of the magnitude x
$E_X(x)$		Exceedance probability of event $e(x)$
F_t(x)		Distribution function of the largest drought event within any given time interval [0, t]
$F_X(x)$		Cumulative distribution function = non-exceedance probability
$H_t(x)$		Distribution function of all drought events within in the time interval [0, t]
i		Rank
$I(t)$	[m^3/s]	Water supply
k		Number of drought events in a predefined time interval
$LAKE$	[%]	Areal percentage of lakes in a catchment
m		Number of class intervals
$MAM(n)$	[m^3/s]	Mean annual n-day minimum
MQ	[m^3/s]	Mean discharge

n		Number of averaging days in the moving average filter
N		Number of observations
O_i		Observed number of observations per class i
p	[%]	Percentage of (discharge) data which exceeds a (discharge) value
p_c		Ratio of the interevent excess volume to the preceding deficit volume
q	[l/(s·km^2)]	Specific discharge
q_S	[l/(s·km^2)]	Specific discharge of summer season
Q	[m^3/s]	Discharge
Q_0	[m^3/s]	Threshold level discharge
$Q90_S$	[m^3/s]	Discharge, which is exceeded 90 % of the summer time = the 90-percentile from the FDC of only summer data
$Q90_Y$	[m^3/s]	Discharge, which is exceeded 90 % of the time = the 90-percentile from the FDC of all-year data
$Q_{min\ i}$	[m^3/s]	Minimum discharge of event i
$Q_{min,S}$		Lowest discharge of summer season
Qx	[m^3/s]	Discharge, which is exceeded x % of the time
r		Number of parameters
r_d	[%]	Specified percentage of the mean drought duration to exclude minor droughts
r_s	[%]	Specified percentage of the mean deficit volume to exclude minor droughts
s_i	[m^3]	Interevent excess volume
t	[s]	Time
T	[years]	Return period
T		Test statistic
t_c	[days]	Critical duration
t_i		Time of occurrence of event i
u		Upper limit above which extreme events are selected
v_i	[m^3]	Deficit volume of event i
v_{pool}	[m^3]	Pooled total deficit volume
$w(t)$	[m^3/s]	Deficit volume series in dimension of the discharge (daily average)

$w_{max\ i}$	[m^3/s]	Deficit volume of drought event *i* in dimension of the discharge
x		Real number
X		Random variable
$Y(t)$	[m^3/s]	Supply-minus-demand series
Z_t		Number of drought event occurring during the time interval [0, *t*]
α		Fraction of the maximal observed deficit volume (criterion to exclude minor drought events)
α		Significance level
ρ		Attained significance level
τ_i	[days]	Interevent time
v		Degrees of freedom

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Zusammenfassung

Die vorliegende Diplomarbeit befasst sich mit der hydrologischen Dürre in Fließgewässern. Da Dürren in Fließgewässern in allen Regionen der Erde mit verschiedenen Klimaten und mit den unterschiedlichsten hydrologischen Regimen auftreten können, wurden sie auf viele verschiedene Arten definiert und entsprechend wurden verschiedene Methoden zur Beschreibung und Quantifizierung von Dürren entwickelt. In dieser Diplomarbeit werden verschiedene Methoden zur Beschreibung von Dürren in Fließgewässern getestet und in Bezug auf die folgenden Punkte beurteilt:

a) Anwendbarkeit auf Abflussdaten von perennierenden, intermittierenden, ephemeralen Fließgewässern;
b) Vergleichbarkeit der Ergebnisse bei Anwendung auf verschiedene Flusstypen;
c) Datenvoraussetzungen und Einschränkungen.

Die Beurteilung basiert auf der Anwendung der zu testenden Methoden auf einen globalen Datensatz, bestehend aus täglichen Abflussdaten für 16 Fließgewässer aus verschiedenen Klimazonen und mit unterschiedlichen hydrologischen Regime.

Zur Beschreibung von Dürren können zwei Konzepte unterschieden werden: (1) die Charakterisierung von Dürren durch Niedrigwasserindices und (2) die Erfassung und Quantifizierung durch Defizitcharakteristika.

Die in der vorliegenden Arbeit getesteten Niedrigwasserindices sind die Perzentile der Abflussdauerlinie (flow duration curve, FDC) und das Mittel aus den jährlichen niedrigsten arithmetischen Mitteln von *n* aufeinander folgenden Tageswerten des Abflusses (mean annual *n*-day minimum, MAM(*n*-day)). Die Ergebnisse für die FDC zeigen, dass die FDC für perennierende, intermittierende und ephemerale Fließgewässer angewendet werden kann und eine gute Methode zum Vergleich der Variabilität von Fließgewässern verschiedener Flusstypen darstellt. Niedrigwasserindices können aus der FDC auch unter der Berücksichtigung des Anteils von abflusslosen Tagen gewählt und verglichen werden. FDCs können aus täglichen Abflusswerten des ganzen Jahres als auch für eine bestimmte Saison berechnet werden. Allerdings können zum Beispiel in frostbeeinflussten Gebieten die FDCs sehr sensitiv zum gewählten Zeitraum der Sommersaison sein.

Der MAM(*n*-day) ist ein geeigneter Niedrigwasserindex für perennierende Flüsse mit und ohne Frosteinfluss, da er weniger sensitiv zur gewählten Sommersaison ist. Allerdings muss

darauf geachtet werden, dass der Jahreswechsel nicht in der Saison der jährlichen Niedrigwasserabflüsse liegt, da sonst manche Tageswerte in zwei aufeinander folgenden Jahren in den MAM(*n*-day) eingehen können. Für intermittierende und ephemerale Fließgewässer ist der MAM(*n*-day) weniger informativ, da er meistens gleich Null ist, außer für große Mittelungszeiträume, *n*.

Von Defizitcharakteristika spricht man, wenn ein Dürreereignis als Unterschreitung eines bestimmten Abflussschwellenwertes definiert wird. Oft verwendete Defizitcharakteristika sind Dauer, Zeitpunkt des Auftretens, Defizitvolumen und Intensität. Außerdem kann eine Frequenzanalyse durchgeführt werden, um das Wiederkehrintervall von Ereignissen einer bestimmten Größe zu bestimmen. Sind zwei Perioden, in denen der Schwellenwert unterschritten wird, nur durch einen sehr kurzen, wenige Tage langen Zeitraum, unterbrochen, werden diese Dürren im Allgemeinen als ein Dürreereignis angesehen. Zur Zusammenfassung dieser so genannten gegenseitig abhängigen Dürren stehen verschiedene Methoden zur Verfügung, so genannte pooling-procedures, wovon ebenfalls mehrere getestet wurden. Die hier getesteten pooling-procedures sind das Interevent-Criterion (IC-method), das Filtern der Abflussserie mit einem gleitenden Mittel aus *n* Tagen (MA(*n*-day)) und der Sequent Peak Algorithm (SPA). Zur Durchführung einer Frequenzanalyse für Dauer und Defizitvolumen von Dürreereignissen wurde das Programm NIZOWKA2003 getestet, welches auf einer von Zelenhasić & Salvai (1987) vorgeschlagen Methode basiert. Dabei wird die kumulierte Verteilungsfunktion für die größte Dürre in einem gegebenen Zeitintervall, z.B. ein Jahr, aus einer partiellen Serie ermittelt.

Die Ermittlung von Defizitcharakteristika aus Tageswerten in Bezug auf einen Schwellenwert ist für ephemerale Fließgewässer in der Regel nicht empfehlenswert, da in diesem Fall Dürren am besten durch die Dauer von abflusslosen Zeiträumen und dem Abflussvolumen von auftretenden Abflussereignissen charakterisiert werden. Auch kann die Verwendung von Jahresmittelwerten empfohlen werden.

Für intermittierende und perennierende Flüsse ergab der Vergleich der verschiedenen pooling-procedures, dass die IC-method in der hier verwendeten Form ungeeignet ist für Flüsse mit starken Abflussschwankungen. Hier berücksichtigt die IC-method als pooling-Kriterium nur die Länge des Zeitraumes zwischen zwei Dürreereignissen, für Flüsse mit starken Abflussschwankungen sollte aber auch das Volumen oberhalb des Schwellenwertes berücksichtigt werden. Mit dieser Einschränkung kann die IC-method für perennierenden und intermittierenden Fließgewässer verwendet werden und liefert vergleichbare Ergebnisse für beide Flusstypen.

Der MA(*n*-day)-Filter kann ebenfalls als pooling-procedure für perennierende und intermittierende verwendet werden und kann insbesondere auch für Fließgewässer mit starken Abflussschwankungen empfohlen werden. Die Ergebnisse sind für alle Flusstypen vergleichbar und somit stellt der MA(*n*-day)-Filter die flexibelste pooling-procedure für globale Vergleiche dar. Ein Nachteil der Methode ist, dass die Abflusszeitreihen durch den Filter modifiziert werden.

Bei der dritten getesteten pooling-procedure, dem SPA, wird das Zusammenfassen von gegenseitig abhängigen Dürreereignissen vom Defizitvolumen und anschließendem Volumen oberhalb des Schwellenwertes abhängig gemacht. Dies macht die Ergebnisse für perennierende und intermittierende Flüsse unvergleichbar, da das Defizitvolumen während abflusslosen Zeiträumen nicht direkt mit dem zu Zeiten mit Abfluss vergleichbar ist. Ein weiterer Nachteil des SPA ist, dass Dürreereignisse, die nach einem großen Ereignis auftreten, leicht mit diesem zusammengefasst werden, ohne allerdings dessen Dauer oder Defizitvolumen zu vergrößern. Der Zeitraum nach einem großen Dürreereignis wird in der Regel als Zeitraum ohne Dürren erfasst. Der SPA ist somit nur zur Erfassung der größten Dürre innerhalb eines Jahres geeignet, nicht aber zur Erfassung aller Dürren. Außerdem können im Vergleich zu den anderen pooling-procedures nur relativ niedrige Schwellenwerte verwendet werden, da Dürreereignisse sonst leicht zu mehrjährigen Ereignissen zusammengefasst werden.

Für die Durchführung von Frequenzanalysen von Dauer und Defizitvolumen kann NIZOWKA2003 insbesondere für perennierende Flüsse ohne Frosteinfluss empfohlen werden. Für frostbeeinflusste Flüsse sollte eine Frequenzanalyse nur auf Basis von Sommerdürren empfohlen werden. Der in NIZOWKA2003 implementierte Weg zur Identifizierung von Sommerdürren ist jedoch nicht optimal, da schwere Sommerdürren, die in lange Winterdürren übergehen unberücksichtigt bleiben. Für eine Frequenzanalyse von Defizitvolumen bei intermittierenden Flüssen sollten abflusslose Zeiten als ‚censored data' behandelt werden. Da dies in NIZOWKA2003 nicht möglich ist, wird es für intermittierende Flüsse nur für Frequenzanalysen von der Dauer von Dürreereignissen empfohlen.

1 Introduction

1.1 Background

‘Drought’ as the word itself is probably understood and heard of by most people, each of them having some kind of visualisation of the word, brown grass, withered crops, dried out river beds, bush fires, empty wells and water holes, navigation difficulties on a stream, or more indirect, higher food prices, restrictions on water usage when showering or using the toilet, or higher energy prices through limited hydropower supply. And each of them realising that droughts can cause severe damage to nature and humans - socially, economically and politically. But when it comes to precisely defining the word it is hard to find a common understanding of it, not only in every-day language but also in a scientific way. The Encyclopaedia of Hydrology and Water Resources (Hersey & Rhodes, 1998) for example mentions among others the following formerly applied definitions: ‘(1) a period of rainfall deficiency, (2) a relative state of forest flammability, (3) occurring when a specific agricultural crop or pasture yields less than expected amounts, (4) denoting a critical level of soil moisture or groundwater depletion, and (5) poetically as a ‘valley of rain deficiency in the broad sweep of time and weather.’’ Despite the diversity of these different drought definitions, they all have in common that they relate in one way or another to a deficit in water, even though they vary in the ‘type of water’ they refer to, e.g. rain, soil moisture, groundwater or streamflow. A current general approach to define the term drought from a hydrological point of view is given in Tallaksen & van Lanen (2004). Here it is said that “drought is *a sustained and regional extensive occurrence of below average natural water availability*”. This implies that a water deficit has to at least last a minimal period of time and cover a certain size of area to be called a drought. It also implies, since it defines drought in a relative way (“below average”), that a drought event can occur in all parts of the world, while its effects can vary considerably. The effects of a drought usually depend on the vulnerability of the affected area. In general droughts become more and more crucial with an increasing demand of water supply for growing populations and developing societies.

The above mentioned view of droughts is not only general in the sense that it applies to all regions of the world but also that it applies to water in all stages of the hydrological cycle. Often different *types of droughts* are distinguished, each referring to a water deficit in a specific part of the hydrological cycle still keeping in mind the connections between them and that a drought in one stage of the cycle can lead to a drought also in other stages. It starts with a less than normal amount of precipitation which is called a *meteorological drought*. After that *soil moisture* droughts and *hydrological droughts* might develop. An agricultural drought is characterised by a low soil water content, which is too low to sufficiently supply cultivated plants. The term hydrological drought is applied to less than normal amounts of water in the different types of water bodies, represented by low water levels in streams, reservoirs and lakes as well as a low groundwater level. Usually, hydrological droughts are further divided into *streamflow droughts* and *groundwater droughts* depending on which type of water body is observed.

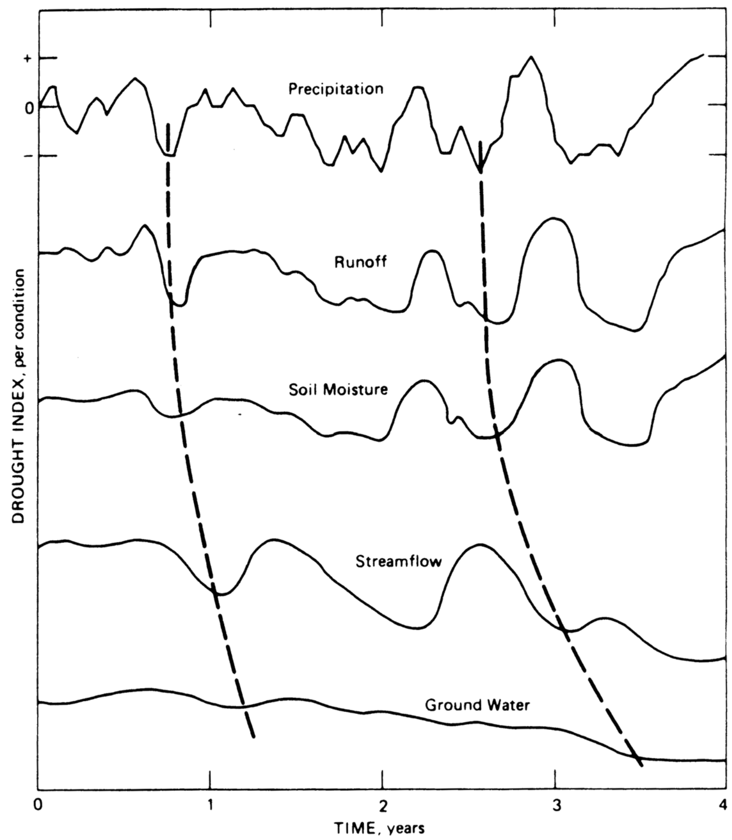


Figure 1.1 Schematic illustration of how hypothetical precipitation deficits and surpluses ideally proceed throughout the hydrological cycle in a delayed and less sharply oscillating way (Rasmusson et al., 1993).

Whether a meteorological drought leads to deficits in soil water, surface water and groundwater, depends not only on the lack of a sufficient water input into the hydrological system of the area (no or too little precipitation) but also on the rate of water losses, naturally, through evapotranspiration or discharge from the area, or artificially, through various kinds of human activities. Apart from potential human activities evapotranspiration is a key factor for the development of droughts, since it can lead to a loss of the received water almost at the same time and place as the input is occurring. The potential evapotranspiration is mostly determined by an interaction of a number of meteorological factors, such as temperature, humidity, wind speed and cloudiness, as well as by the water demands of plants. The actual evapotranspiration additionally depends on "catchment characteristics, e.g. land use, soils and water-table depth" (van Lanen et al., 2004). For the development of soil moisture droughts, precipitation deficit and high evapotranspiration are the two most important factors and usually the soil moisture drought is the next one to start after a meteorological drought. For the development of a hydrological drought additional catchment characteristics are decisive, such as topography and hydrogeology. Whether the streams or the groundwater react first to a deficit in other parts of the hydrological cycle depends again on the hydrogeology of a catchment. When a stream is mostly groundwater fed streamflow and groundwater droughts can occur at a similar time. However, it is more common that the surface waters react first (Tallaksen & van Lanen, 2004). Figure 1.1 illustrates schematically how hypothetical precipitation deficits and surpluses ideally proceed throughout the hydrological cycle in a delayed and less sharply oscillating way. The presented components of the hydrological cycle are precipitation, runoff, soil moisture, streamflow and groundwater. This study focuses on streamflow.

Knowledge about streamflow droughts is important for a variety of tasks, e.g. reservoir management for drinking water supply or electricity production, water quality considerations or navigability of streams. A single streamflow drought event can be described through several *drought characteristics* such as duration, time of occurrence, starting and ending date, severity and minimum flow, and when looking at the series of all drought events in a specified period of time, also through its frequency or return period. To derive these characteristics many different methods have been developed, which also imply varying definitions of what exactly is considered to be a drought. This is mainly because streamflow drought is a world wide phenomenon, occurring in all types of climate zones and affecting rivers with different types of hydrological regimes. Researchers in different parts of the world thus have to cope with a number of different features and effects of streamflow droughts. For example in a fast responding tropical catchment a few days without rain might lead to a streamflow drought whereas in a semi-arid climate a stream could fall dry for several months and might still not be considered to be in a drought situation. Consequently, a method to derive streamflow drought characteristics developed in one region is not necessarily appropriate or even applicable in another region. In the semi-arid region for example, a good way of characterising drought events might be the duration of zero-flow periods, in other regions however, streams never fall dry and one would conclude that these streams never experience a drought. Different methods of deriving streamflow drought characteristics are therefore needed in order to precisely describe the whole variety of streamflow droughts and for at-site drought studies one has to be careful selecting a method that suites the characteristics of the stream under study. The selection of an appropriate method can be even more difficult when drought events of several streams within one region are to be analyzed. But analyzing and comparing them could be very useful in order to gain a better understanding of the processes involved in streamflow drought development and to eventually reduce the damages caused by droughts through an accurate prediction of drought events and a more sustainable water management. It therefore can be useful to know which method of deriving streamflow drought characteristics can be applied for what kind of hydrological regimes.

1.2 Objective

It is the main objective of this Diplomarbeit to give an overview over different methods to derive streamflow drought characteristics and to evaluate the applicability of these methods for streams with different types of hydrological regimes. The methods are evaluated according to their:

a) applicability for drought studies of perennial, intermittent and ephemeral streams, i.e. testing for which of the stream types a method gives meaningful and significant information;
b) general applicability, i.e. evaluating the results from point a), whether a method can be used to compare different types of streams;
c) data requirements and limitations.

The evaluation is based on the information gained by applying the methods to a global data set representing different hydrological regimes as well as different climate zones. The data requirements and limitations can depend on the particular methodology as well as they can be introduced by data properties of a stream type.

1.3 Framework of the master thesis

The study has been conducted within the framework of the ASTHyDA project, a research project of the northern European FRIEND low-flow group, funded by the EC as an Accompanying Measure in the EC's 5th Framework Programme. ASTHyDA stands for Analysis, Synthesis and Transfer of Knowledge and tools on Hydrological Droughts Assessment through a European network. It "addresses, through a consortium of primarily European experts, the need for a concise review and dissemination of recent knowledge and tools for prediction of streamflow and groundwater in periods of water scarcity." (http://drought.uio.no, 2003). The Diplomarbeit contributes to one of the project's aims, which is "to encourage harmonization of methods and provide recommendations for tools for drought estimation, monitoring, forecasting and mitigation" (http://drought.uio.no, 2003).

1.4 Thesis outline

This thesis is divided into five chapters, of which this is the first one. In includes a introduction into hydrological droughts as well as an outline of the main objective of this thesis. In Chapter 2, different concepts of studying droughts are introduced and the particular methods which are evaluated in this study are described. The data is introduced in Chapter 3, where also important data considerations for drought studies are discussed. Chapter 4 contains the results of the application of the different methods as well as the evaluation of each method. The conclusions are presented in Chapter 5.

2 Streamflow drought characteristics

2.1 Concepts

A streamflow drought is said to be a period during which the discharge is below normal or, in a demand orientated study, a period during which the discharge is insufficient. In both cases droughts are characterized through low flow values and a clear differentiation between droughts and low flow periods has to be made.

The term '*low flow period*' usually refers to the regime of a stream, which represents the average annual cycle of the streamflow, and the terms 'low flow period' and 'high flow period' are used to describe the normal annual fluctuations of streamflow linked to the annual cycle of the regional climate. Depending on the climate the regime of a stream can show one or more low flow and high flow periods. The equatorial climate for example is marked by two rainy and two dry seasons and streamflow regimes have two corresponding high flow and low flow periods (McMahon & Diaz Arenas, 1982), while a monsoon climate causes only one low flow and one high flow period.

Droughts on the other hand are not necessarily a seasonal characteristic of a streamflow regime. They are prolonged periods with unusually low streamflow, which do not have to occur each year. For example in a Mediterranean region the summer months June till October could be the low flow period of a stream, but only in dry and hot summers the stream would experience droughts. So there can be years passing without the occurrence of any drought events and there can be years when one or several droughts occur. But there exist also droughts which last only a few days and droughts which last several months, several seasons or several years. Often a period of unusually low streamflow has to last a defined minimal period of time to be considered a drought. Depending on the climate of a catchment only periods of below normal discharge compared to the low flow part of the regime are considered to be droughts, whereas deviations from the high flow part are rather called 'streamflow deficiency' or 'streamflow anomaly' (Hisdal, 2002). This is usually the case for a catchment in a temperate climate region, where a streamflow deficiency compared to the high flow part of the regime usually have no severe consequences. In a semi-arid region on the other hand, one is used and prepared to long periods of low or even no streamflow during the dry season and the interest of water management engineers lies in the water quantities of the wet season. In a semi-arid region a drought study might therefore also be focusing on the high flow season and streamflow deficiencies in the high flow season can either be considered as droughts themselves or as the cause of a subsequent drought during the dry season.

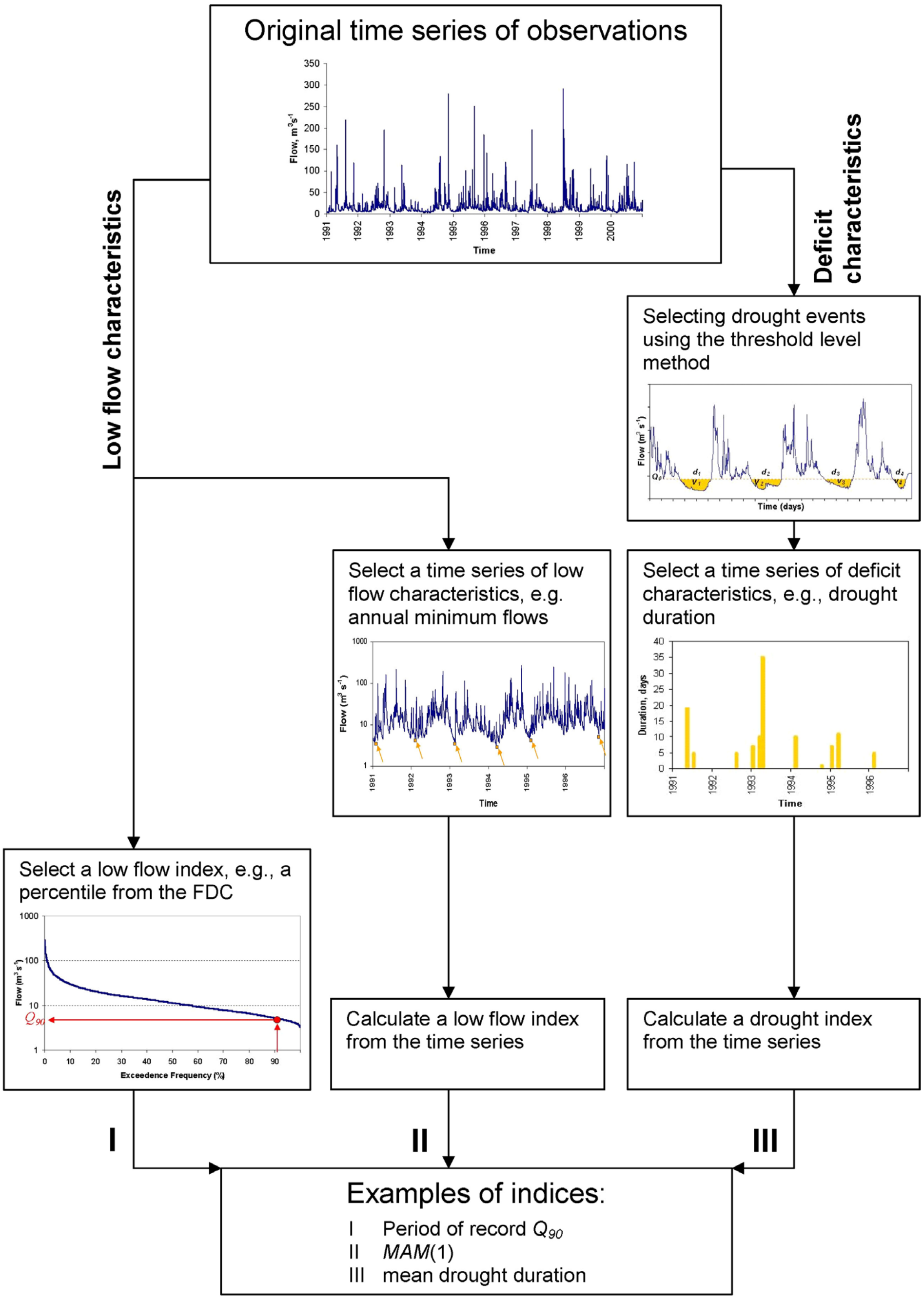


Figure 2.1 Possible ways of deriving drought characteristics (Hisdal et al., 2004).

Drought studies have been based on many different concepts and two main ways of approaching the drought topic can be distinguished (Figure 2.1) (Hisdal et al., 2004). One way is to study droughts on the basis of *low flow characteristics* (paths I and II in Figure 2.1), such as a time series of the annual minimum *n*-day discharge, *AM*(*n*-day) (Section 2.2.2) or a percentile from the flow duration curve (FDC) (Section 2.2.1), which describe the low flow part of the regime. To study droughts extremes of the low flow characteristics are chosen. These approaches identify and characterise droughts only according to one of their statistical properties, which is their magnitude expressed through the discharge (Tallaksen et al., 1997). They do not necessarily look at the discharge as a time depending process or they look only at a predefined period of it, e.g. *n* days.

The second way of studying droughts is to look at the discharge series as a time depending process and to identify the complete period of a drought event, from its first day to the last one. In this way a series of drought events can be derived from the discharge series and the drought events can be described and quantified by a number of different properties, so called *deficit characteristics*, such as drought duration (path III in Figure 2.1). One possibility to define drought events is as “the longest periods which are necessary to yield a specified small percentage (1-10 %) of the mean annual runoff” (Smakhtin, 2001). Other possible procedures, and according to Bonacci (1993) the most commonly applied ones, introduce the use of a threshold or truncation level, Q_0. A discharge value is chosen as threshold level and in the most basic form of this concept a stream is defined to be in a drought situation at times when the discharge is below the threshold level. The threshold level element is used in the so called threshold level method as well as in the Sequent Peak Algorithm (SPA), which are both evaluated in this study and introduced in more detail in Sections 2.3.1 and 2.3.2 respectively. The properties characterising drought events are called ‘deficit characteristics’, since they describe a specific period during which the discharge is in a deficit, for example as compared to the threshold level. The most commonly applied deficit characteristics are the drought’s time of occurrence, its duration, its deficit volume or severity, and the minimum flow occurring during the drought event. Sometimes also the drought intensity is considered, which is the ratio of the deficit volume and drought duration. The time of occurrence of a drought event has been expressed in several ways, for example as the date of the first day of the drought, the median date or the date of the day with the minimal flow (Hisdal et al., 2004). In regional studies also the areal coverage is of interest and for planning tasks the extreme events and their return periods are very important. One has to aware that in order to describe a drought or a time series of droughts completely also the chosen threshold level and its meaning have to be mentioned, since for example duration and deficit volume of the detected droughts vary with the chosen height of the threshold level.

The main emphasis of this study lies on the evaluation of methods to derive deficit characteristics, since more work on low flow characteristics already exists.

Time resolution of the data series

Choosing an appropriate concept to study droughts depends also on the time resolution of the available data and vice versa the most favourable time resolution depends on the purpose and outline of the study, the characteristics of the streams under study, the methods one wants to apply, and the available computing tools. A daily time series of course contains more detailed information about the stream's discharge and about drought events, but also discharge series with a larger time interval can be favourable for various reasons. In the past, hydrological drought studies have been based on anything from daily up to annual time series. In general, local scale data records often have a resolution of days or months and local studies are preferentially based on high resolution data, whereas studies with a larger spatial coverage and/or temporal extent are often based on time-aggregated seasonal or annual date (Stahl & Hisdal, 2004).

The droughts themselves are prolonged periods and a single drought event can last a couple of days, several years or any time period in between. Therefore when choosing the appropriate time resolution, a important aspect to consider is the duration of the studied droughts. In a semi-arid climate a dry period might only considered to be a drought when it lasts for more than a year while in a humid climate some streams might never experience multi-year droughts. In the first case, a statistical description of long multi-year droughts might be conducted much more easily when based on annual data, especially when it comes to identify return periods of the observed drought events, and a time series with annual resolution might be favourable. Whereas in the second case, annual data might not reveal even the most severe drought events, for example if an unusually dry summer is followed by an unusually wet winter, the mean annual discharge might not show any deviation from normal. Another problem with annual data is, as Bonacci and Štambuk observed in Croatia (Bonacci, 1993), that the time of occurrence of a drought can not be identified and the conclusions about its effects are restricted, e.g. it cannot be identified whether a drought occurred during the growing season or not. Bonacci (1993) recommended the month as a suitable time interval for drought studies for agriculture, water supply and groundwater levels, since it contains much more detailed information than the year, and at the same time it is a long enough time interval, in contrast to the day, to eliminate all less significant events, so called *minor droughts*. To include minor events in the drought series is not a problem in itself, it rather provides additional information, but if the drought series is used for a frequency analysis of extremely severe events, a high number of minor droughts might distort the analysis (Tallaksen et al., 1997). Then minor droughts should be excluded from the used drought series. Possible ways of excluding minor droughts are discussed together with the threshold level method in Section 2.3.1.

A second disadvantage of using a daily discharge series besides obtaining minor drought events is that during a prolonged period of low discharge several drought events which are only a short time apart from each other might be observed. These drought events are considered to be mutually dependent. Generally, one would consider two drought events which are only one or two days apart from each other rather as one large event than as two small ones and these events should be pooled. Also for many statistical procedures is independence of successive events a common prerequisite. For the threshold level method procedures to combine mutually dependent droughts, so called *pooling-procedures*, have been developed. These procedures are explained together with the threshold level method in Sections 2.3.1 and 2.3.2.

2.2 Low flow indices

2.2.1 Flow duration curve (FDC) and percentiles

The flow duration curve (FDC) displays for all observed discharge values the percentage of time during which higher discharge values are observed. As such it plots the discharge above its exceedance frequency (Figure 2.2). In other studies the exceedance frequency is frequently defined as the 'percentage of time a value is equalled or exceeded' rather than 'it is exceeded'. This definition has for example been used by Vogel & Fennessey (1994) or Zelenhasić & Salvai (1987). A discharge value which is exceeded in x % of the time is referred to as the x-percentile of the FDC, Qx. The FDC describes the discharge variability of a stream and allows an easy visual comparison of discharge variabilities of different streams when several standardised FDCs are plotted together in one graph. A common way of standardising a FDC is to divide the discharge values by the value which is exceeded in 50 % of the time, $Q50$. For intermittent and ephemeral streams this value can be equal to zero and then mean discharge (MQ) applied for the standardisation. When the variability of the discharge series is high, a $\log_{10}$-scale on the discharge-axis can be helpful. But of course it can not be used for intermittent or ephemeral streams, when discharge values of zero are to be plotted.

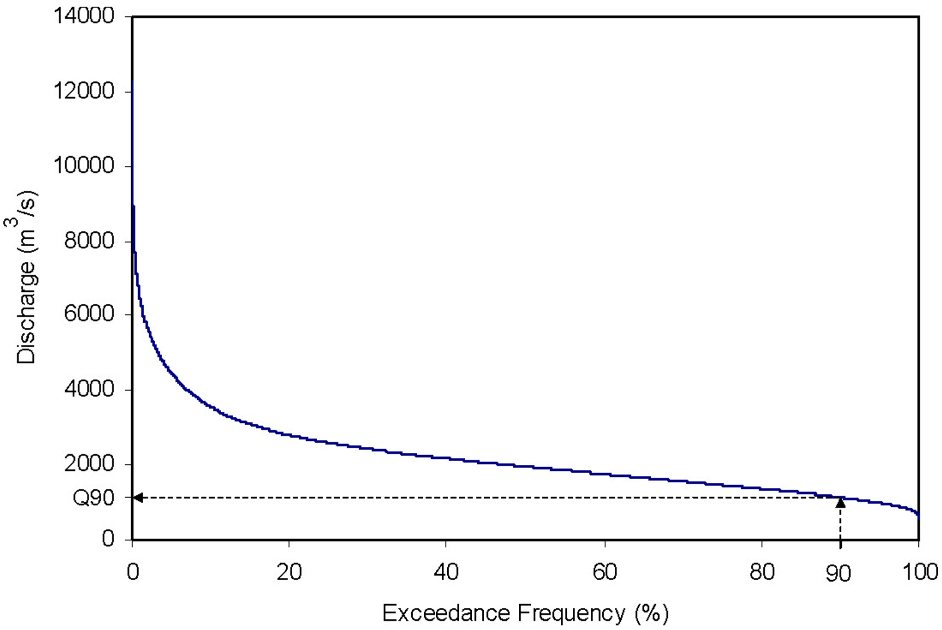


Figure 2.2 Flow duration curve of the River Rhine at Lobith, the Netherlands, 1901-1993.

Low flow indices derived from the FDC are the percentiles which indicate a high frequency of exceedance and therefore present the low flow period of a regime. Common percentiles used as low flow indices are the 95-, 90- and 70-percentile, $Q95$, $Q90$, and $Q70$ respectively. They are also frequently chosen as value for the threshold level in drought event definitions.

A FDC can be calculated for data with any kind of time step and for any record length. Most commonly the whole period of record is used. The FDC is calculated by assigning each discharge value its rank, i in descending order, which means that the largest value gets rank 1, and then the values are plotted over p, which is the percentage of data which exceeds a value.

$$p = \frac{i}{N} \tag{2.1}$$

where N is the total number of values. The percentile Qx is assigned the discharge value Q with the smallest p which is equal or greater than x.

$$Qx = Q(\min(p \geq x)) \tag{2.2}$$

One has to be aware that, if the number of values is even, there can be a difference between the $Q50$ according to this definition and the median as often defined in statistical literature. The median there is calculated as the average of the two middle values of the sorted series (e.g. Bhattacharyya & Johnson, 1977), while the $Q50$ is the lower one of these two values.

Instead of using all the data, a FDC can also be calculated for example for a specific season by taking only all the summer or the winter values of the time series, calculating a FDC_S or FDC_W respectively. Accordingly, all-year, summer and winter percentiles can be distinguished, Qx_Y, Qx_S and Qx_W.

As Vogel & Fennessey (1994) pointed out, a FDC, which is obtained from the whole period of record, can not be interpreted to represent the distribution of the yearly flow, only the distribution of the period of record, which is of course the more informative the longer the period of record is. They suggested an alternative way of calculating FDCs for each year of record separately, which allows an annual interpretation as well as the calculation of confidence intervals and recurrence intervals.

2.2.2 Mean annual minimum n-day discharge (MAM(*n*-day))

The annual minimum *n*-day discharge, *AM*(*n*-day) is the smallest average discharge of *n* consecutive days within one year. Common averaging interval, i.e. values of *n*, are 1, 7, 10, and 30 days. An AM(*n*-day) can easily be calculated by applying a moving-average filter of *n* days on a daily discharge series and subsequently selecting the minimum of the filtered series. Calculating AM(*n*-day)s for several years, the obtained *AM*(*n*-day)-time series is the basis for a frequently used low flow index, the mean annual minimum *n*-day discharge, *MAM*(*n-day*), which is the average of the *AM*(*n*-day)-time series. In contrast to percentiles from the FDC the MAM(*n*-day) implies a duration aspect, included in the averaging interval.

In the United States, the most widely used low flow index is the 10-year annual minimum 7-day discharge $AM(7\text{-day})_{10}$ (Hisdal et al., 2004), which is the *AM*(*7*-day) with a return period of 10 years. To obtain this value a frequency analysis is carried out on the *AM*(*7*-day)-time series and the value, which is on average observed every 10 years is chosen.

2.3 Deficit characteristics

2.3.1 Threshold level method

The threshold level method originates from the theory of runs as introduced by Yevjevich in 1967 (Smakhtin, 2001). Yevjevich originally defined droughts as periods during which the water supply does not meet the current water demand, and both the water supply, *I*(*t*) as well as the water demand, *D*(*t*) were expressed as time series with the same temporal resolution (Figure 2.3). A time series of drought events is then obtained through the series of uninterrupted sequences of negative values of the supply-minus-demand time series, $Y(t)$. Each uninterrupted sequence of negative values constitutes one drought event.

$$Y(t) = I(t) - D(t) \tag{2.3}$$

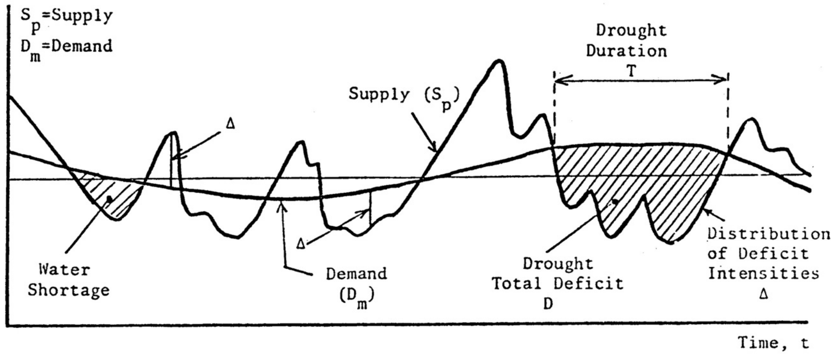


Figure 2.3 Supply-minus-demand series for the definition of droughts (Yevjevich, 1983).

The statistical problem arising from this definition was the complexity of the supply-minus-demand series. Usually $I(t)$ is a stochastic or periodic-stochastic process and $D(t)$ a trend-periodic-stochastic process. This results in the $Y(t)$ series as a trend-periodic-stochastic-process, with periodicity and stochasticity from both, supply and demand time series and trend mainly coming from the demand time series (Yevjevich, 1983). And according to Yevjevich (1983) "the application of the theory of runs to complex trend-periodic-stochastic processes has not yet been developed to a degree of a reliable current use." In order to be able to describe the supply-minus-demand series in a statistically correct way, Yevjevich simplified the concept by applying a constant demand (Yevjevich, 1983). The demand is now represented by a threshold level, Q_0 and droughts are defined as periods during which the discharge is below the threshold level.

In Figure 2.4 commonly used deficit characteristics are introduced as defined by the use of a threshold level. These are: the time of occurrence, t_i, drought duration, d_i, deficit volume or severity, v_i, and the minimum flow occurring during the drought event, $Q_{min\ i}$.

The application of a threshold level allows both, defining drought events as periods with discharge below normal as well as identifying periods with insufficient water supply for a specific demand. In the latter case the threshold level is set equal to the discharge demand, but in the former case it is considered to represent 'normal' conditions, which means that it can be chosen more or less freely corresponding to the stream under study as well as the task of the study. It is however common to apply as a low flow index an objective and comparable value for the threshold level. Frequently used threshold levels are *Q*95, *Q*90 and *Q*70 and for streams with a high percentage of zero-flow values the mean discharge, *MQ* or percentiles as high as *Q*30 or *Q*10.

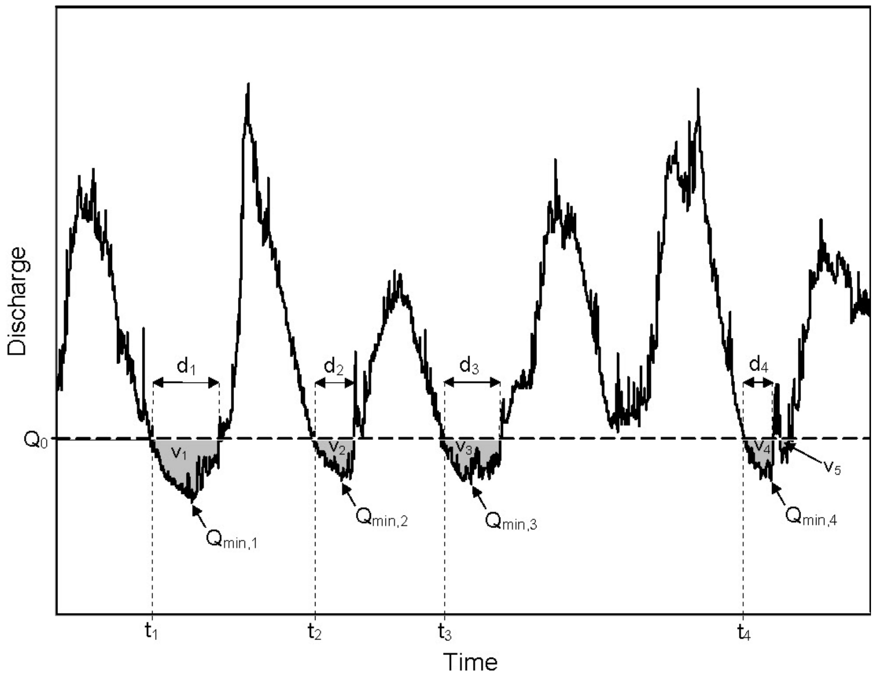


Figure 2.4 Illustration of commonly used deficit characteristics as defined with the threshold level method: time of occurrence, t_i, duration, d_i, deficit volume or severity, v_i, and the minimum flow occurring during the drought event, $Q_{min\ i}$.

Yevjevich originally introduced the method for discharge time series with a time resolution of one month or longer, but later on it was also applied on daily discharge series, e.g. by Zelenhasić & Salvai (1987) and Tallaksen et al. (1997). When it is applied to series with a daily resolution the most detailed information about a stream is provided, but as opposed to series of longer resolutions two special problems have to be considered, as stated in Section 2.1. These problems are the including of minor droughts in the drought series as well as a potential mutual dependency of successive drought events. Mutually dependent drought events can be pooled with the help of pooling-procedures. The pooling-procedures discussed here are the interevent criterion (IC), the moving average filter (MA) as well as the Sequent Peak Algorithm (SPA). The pooling-procedures remove minor droughts to some extent at the same time as they pool mutually dependent droughts, but usually minor droughts have to be removed separately subsequent to pooling.

In literature several methods for the removal of minor drought events have been suggested. Tallaksen et al. (1997) for example excluded all droughts which lasted less than a certain percentage, r_d of the mean drought duration or had a smaller deficit volume than a specified percentage, r_s of the mean deficit volume. The optimal values for the factors r_d and r_s might vary for different distributions of observed drought events, and therefore the same parameters can not necessarily be used for all kind of streams. Zelenhasić & Salvai (1987) excluded all droughts which are smaller than a certain fraction, α of the maximal observed deficit volume and recommended to set α to 0.01 or 0.005. The disadvantage of this method is that α is very sensitive to outliers. And when a large number of droughts are excluded from the series, because they are considered to be minor droughts, one might end up with too few events to conduct a proper frequency analysis. Another possibility is to remove all drought events which last less than a defined number of days, d_{min}.

2.3.1.1 Interevent criterion (IC)

The interevent criterion consists in most cases of an interevent time as well as an interevent volume criterion, since two successive drought events, e_i and e_{i+1}, are considered to be mutually dependent when the interevent time as well as the excess volume between them are small compared to their duration and deficit volume. When e_i and e_{i+1} are mutually dependent, they should be pooled to one large drought event.

Zelenhasić & Salvai (1987) introduced the *interevent time criterion*. They considered two drought events to be dependent of each other, when the number of days the discharge between two drought events exceeds the threshold is less than or equal to a predefined critical duration t_c. So two successive droughts are pooled, when:

$$\tau_i \leq t_c \tag{2.4}$$

where τ_i is the time between the two drought events e_i and e_{i+1}. Zelenhasić & Salvai (1987) used a critical duration of t_c = 6 days.

The combined application of an interevent time criterion together with an *interevent volume criterion* was suggested later on by Madsen & Rosbjerg in 1995 (Tallaksen et al., 1997). The interevent volume criterion has been implemented in different ways, for example its critical value can be set as an absolute value in m^3 or it can be a relative value expressed as a fraction, p_c of the deficit volume of the preceding drought. Tallaksen et al. (1997) applied a combination of the two interevent criteria and determined the optimal values of t_c and p_c for two perennial streams in Denmark. In order for two droughts to be pooled both criteria had to be fulfilled: the interevent time had to be less than or equal to t_c and the ratio of the interevent excess volume, s_i and the preceding deficit volume, v_i had to be less than p_c. Tallaksen et al. found the optimal criteria combination to be t_c = 5 days and p_c = 0.1. The optimisation process was based on the following definitions of the pooled total drought duration, d_{pool} and pooled total deficit volume, v_{pool}.

The duration of the pooled total drought event, d_{pool} lasts from the first day of the first pooled event to the last day of the last pooled event, including the interevent periods:

$$d_{pool} = d_i + d_{i+1} + \tau_i \tag{2.5}$$

where d_i is the duration of event e_i and τ_i is the time between the two drought events e_i and e_{i+1}. The total deficit volume of the pooled events is the sum of the single deficit volumes, v_i minus the interevent excess volume, s_i:

$$v_{pool} = v_i + v_{i+1} - s_i \tag{2.6}$$

Zelenhasić & Salvai (1987) on the other hand calculate the pooled total duration only from the sum of the single drought events without adding the duration of the interevent excess periods and the pooled total deficit volume from the sum of the single drought events without subtracting the interevent excess volume. The two drought characteristics then become:

$$d_{pool} = d_i + d_{i+1} \tag{2.7}$$

$$v_{pool} = v_i + v_{i+1} \tag{2.8}$$

Since the interevent time and volume are small compared to the total duration and deficit volume the results of the two ways of calculating the total duration and total deficit volume deviate only slightly, but nevertheless results derived in the different ways can not be equated and for comparisons always the same method should be applied. For studies focusing on reservoir management the first way of calculating the total pooled deficit volume, $v_{pool} = v_i + v_{i+1} - s_i$ is the more consistent way, correctly describing the process of withdrawal and refilling of the reservoir.

In this study the program NIZOWKA2003 was applied for the derivation of drought events using the threshold level method. NIZOWKA2003 further offers a frequency analysis of drought duration and deficit volume and to evaluate its applicability was a major aspect in this study. NIZOWKA2003 offered the following ways of calculating the total pooled deficit characteristics:

Duration: $d_{pool} = d_i + d_{i+1}$ or $d_{pool} = d_i + d_{i+1} + \tau_i$ (2.9)

(real drought duration) (full drought duration)

Deficit volume: $v_{pool} = v_i + v_{i+1}$ (2.10)

For the total pooled duration the full drought duration, since it more precisely defines the period from the first day of the drought until the drought ends.

2.3.1.2 Moving average filter (MA-filter)

From the pooling-procedures described here, the moving average-filter (MA-filter) is the one which most effectively removes also minor droughts at the same time as it pools dependent drought. A MA-filter smoothes the original series, since the filtered discharge value for one day is calculated as average from the *n* days before and after it. In this way short periods of original discharges above the threshold level between two drought events can be smoothed to discharge values below the threshold level and the two successive drought events become pooled (Figure 2.5). One has to be aware that by calculating daily values as average from *n* days it can easily happen that one introduces dependency between drought events (Hisdal et al., 2004). This happens when one event occurs less than *n* days after the preceding one. Then the last values of the first event are calculated from some of the same days as the first values of the second event, which makes the two events mutually dependent. To obtain a drought series of mutually independent events one can apply the *MA*(*n-day*) filter together with an additional IT-criterion**.**

This method is superior to the IT method in the way that the distance between two drought events as well as the magnitude of the discharge values below and above the threshold level determine the pooling of the two events in one step. Also the excess volume is automatically subtracted from the total deficit volume. In the same way as minor periods above the threshold level are smoothed away by the MA filter and dependent droughts are pooled, the filter also smoothes away minor periods below the threshold level and thereby removes minor droughts. For the two perennial streams in Denmark Tallaksen et al. (1997) found a MA of 10 days to be optimal to pool single drought events. Tate et al. (2000) applied a MA(10-day)-filter to data from 15 stations in the Southern African region, which had during 0 - 95 % of the time zero discharge, but they also optimized *n* only for a selection of three streams which all had zero discharge in less than 1 % of the time.

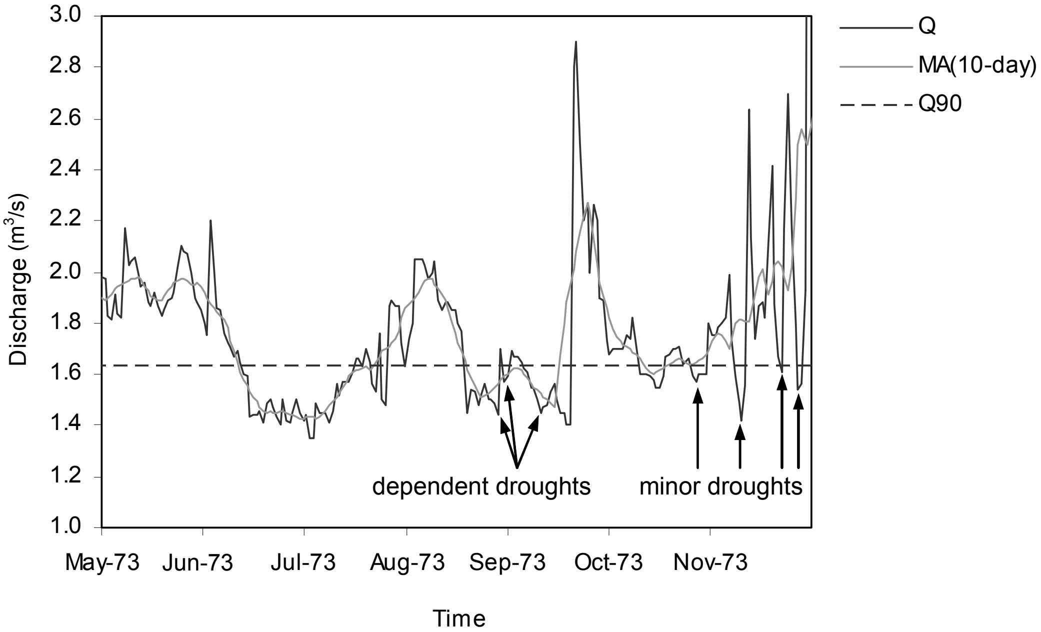


Figure 2.5 Illustration of the pooling of mutually dependent droughts and the removal of minor droughts by an MA(10-day)-filter at $Q_o = Q90$.

2.3.2 Sequent Peak Algorithm (SPA)

The Sequent Peak Algorithm has been developed for engineering purposes to calculate the needed storage volume of water reservoirs. It derives from a time series the maximal observed deficit volume during the recorded time period in terms of the maximal amount of water which would have been needed to be stored in the reservoir at one time to be able to constantly maintain a minimum discharge at the level of the threshold, Q_0 (Figure 2.6).

A time series of the deficit volume, $w(t)$ in the dimension of the discharge is calculated in the following way:

$$w(t) = \begin{cases} w(t-1) + Q_0 - Q(t) & \text{if} \quad w(t-1) + Q_0 - Q(t) > 0 \\ 0 & \text{if} \quad w(t-1) + Q_0 - Q(t) \leq 0 \end{cases} \tag{2.11}$$

$w(t)$ can also be seen as the subtraction of water volume from the reservoir, Q_0 as the desired yield and $Q(t)$ as input. When $Q(t)$ is below Q_0, the deficit volume $w(t)$ increases and the stored reservoir volume becomes less, when more than the required output is flowing into the reservoir, the reservoir fills up again, but not necessarily all the way to its original volume. The reservoir volume continues to fluctuate depending on the input discharge being higher and lower than Q_0. Only when the reservoir is filled up again to its original volume (or the deficit volume $w(t)$ is back to zero again) a drought is said to be finished. The maximal observed deficit volume, v_{Max} is then the maximum of $w(t)$ converted into the dimension of volume.

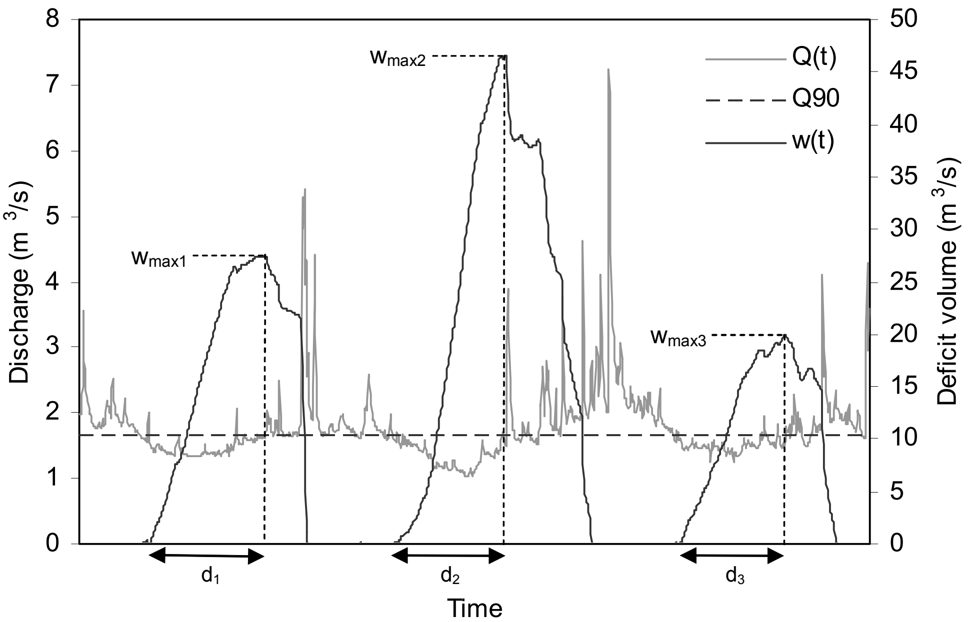


Figure 2.6 Illustration of the derivation of the deficit characteristics duration, d_i and deficit volume, $w_{max\ i}$ by the SPA at $Q_o = Q90$ (Data from Lindenborg Bro, Mar 1975 – Feb 1978).

The SPA can also be used as a pooling-procedure for daily discharge series in connection with the threshold level method. Single periods with $Q(t) < Q_0$ are pooled as long as $w(t)$ has not yet gone back to zero again. When $w(t)$ has gone back to zero, or the reservoir volume has reached its original height again, successive droughts are considered to be mutually independent. The total deficit volume, $w_{max\ i}$ of any pooled drought event in the series is then the maximum of $w(t)$ between two successive days with $w(t) = 0$. When $w_{max\ i}$ is given in (m^3/s), the total pooled deficit volume in (m^3), v_i is calculated by multiplying $w_{max\ i}$ with the numbers of seconds per day. The duration, d_i of the drought event is the time period from the first day of $w(t) > 0$ until the day when $w(t)$ reaches its maximum $w_{max\ i}$.

2.4 Frequency analysis

In a frequency analysis a theoretical probability distribution is fitted to a series of observed events in order to determine the probability of the occurrence of events of any defined magnitude. In drought studies frequency analysis can for example be conducted for low flow characteristics, e.g. AM(*n*-day)-values, as well as for deficit characteristics. This study focuses on the two deficit characteristics deficit volume and duration, where the largest events are of interest. In the following the frequency analysis is described for maximum values, since the analysed deficit characteristics are maximum values.

One way of expressing the probability of an event *e* with a magnitude *x, e*(*x*) is to calculate its *return period, T*(*x*). *T*(*x*) is the average time interval between successive events with a magnitude larger than *x*. This means that an event of a magnitude exceeding *x* will on average occur once in *T* years. The event *e*(*x*) is called a *T*-year event. The return period of an event *e*(*x*) can be calculated from its cumulative probability $F_X(x)$ in the following way:
From the cumulative probability the exceedance probability, $E_X(x)$ of *x* can be calculated:

$$\begin{aligned} F_X(x) &= \Pr\{X \le x\} \\ E_X(x) &= \Pr\{X > x\} = 1 - F_X(x) \end{aligned} \tag{2.12}$$

which then gives the return period

$$T(x) = \frac{1}{E_X(x)} = \frac{1}{1 - F_X(x)} \tag{2.13}$$

T-year events are often used as design events to dimension the size of water related structures, such as water reservoirs or dams. Depending on the kind of structure a design event could be a 100-year, 200-year or even 1000-year event. This means that one is usually interested in the return periods of the extreme events and a frequency analysis should be conducted on those. A series of drought events can for example be selected by the threshold level method as described in Section 2.3.1. The first step of a frequency analysis is to select the extreme events from a time series of events, for which a variety of selection methods exist. The second step is to check whether the selected events fulfil the theoretical assumptions of a frequency analysis, which is that the data are identically and independently distributed (iid). The third step is to choose a probability distribution which is appropriate for the selected extremes. Then the probability distribution is fitted to the observed events by estimating the parameters of the distribution. Finally, the quality of how well the estimated distribution fits to the observed events can be tested by a goodness-of-fit test. The derived probability distribution function can then be used to calculate the magnitude of events with a desired return period.

1. Selection of extreme events

   There are several common ways of selecting the extreme events from a time series of events. For example the extreme events can be selected as an annual maximum series

(AMS) or as a partial duration series (PDS). For the AMS the largest event of each year is chosen. For a PDS all events which exceed a predefined magnitude are considered. This magnitude which has to be exceeded is called the *upper limit*, *u*. The selection of a subset of extreme events which exceed an upper limit can also be seen as an additional way of excluding minor drought events from the series. Thus it can for example be realised by applying higher values for the criteria to remove minor droughts.

Both, the AMS as well as the PDS, have advantages and disadvantages. The main disadvantage of the AMS is that in some years several extreme events can occur, which are all more extreme than the most extreme event in another year, but only the most extreme one will be considered. One is therefore likely to end up with a smaller number of extreme events than in a PDS. This is especially a disadvantage when the series is short, since a low number of events decreases the accuracy of the estimation considerably. Another disadvantage of AMS is that one is forced to select one event each year, which means that in a year when no extreme event occurs a non-extreme event will be chosen and the selected series can not anymore be considered to be identically distributed. The use of AMS therefore often requires an additional step to filter out the non-extreme events. This step is similar to the upper limit as introduced for the PDS.

The disadvantage of the PDS is that the risk of dependency between successive events is higher than in the AMS. Mutually dependent droughts should be pooled to one event independent of the preceding and succeeding events. In many regions, where no long records of hydrological data exist, the advantage of the PDS including more events is important, and a frequency analysis based on a PDS is often favourable.

2. Checking for iid

   The basic assumption for a statistically correct frequency analysis is that the events are identically and independently distributed. For the events to be identically distributed they have to belong to the same population. This means that the events have to be caused by the same processes, which might not be the case in regions with strongly seasonal climate, causing seasonality in the time series of drought events. Independence of the drought events requires that there is no serial correlation in the time series of drought events and that the hydrological regime remains stationary during the period of record (Tallaksen et al. 2004). The check for stationarity of the discharge data as well as how to deal with seasonality in the time series of drought events are discussed in Section 3.2.2. No matter which precautions have been taken to assure that the derived drought event series is iid, one should always have a look at the histogram of the events, in order to get to know the data one is working with and also to check visually whether the data clearly belong to the same population and can be estimated with a single probability distribution model.

3. Probability distribution functions

   For drought studies a variety of probability distribution models have been applied, but when selecting an appropriate distribution one should consider several aspects. One aspect is that distributions adapt the better to a data sample, the more parameters they have, but this simultaneously reduces the reliability in the estimate of the parameters. Generally, distributions with up to three parameters are recommended (Tallaksen et al., 2004). How well a fitted distribution adapts to the data sample can be judged by graphical or statistical methods. Often a number of distributions can be considered to fit the data satisfactorily, but the majority of methods does not allow a comparison of different distributions (Tallaksen et al., 2004). Additionally, many distributions are quite similar in their middle parts but vary considerably in their tails (Tallaksen et al., 2004). The tails describe the extreme events and are therefore essential for the estimation of design events with higher return periods, but the commonly low number of observations of extreme events makes it hard to decide which distributions fits well also in the extreme range. It is therefore important to consider the theoretical knowledge about the distributions as well as about the observed phenomenon. For deficit volume and duration of droughts, a distribution which is bounded above might be favourable, provided that no multi-year droughts are present (Tallaksen et al., 2004). The theoretical solution to the distribution of a PDS is that it can be approximated with a Generalized Pareto distribution, provided that the chosen upper limit, u for the derivation of the PDS is high enough (Pickands, 1975). The Generalized Pareto distribution is bounded in the extreme end in the case that its shape parameter is greater than zero. When the shape parameter is equal to zero, it is reduced to the Exponential distribution (Tallaksen et al., 2004).

4. Goodness-of-fit test

   A goodness-of-fit-test tests whether the deviation between the observed data and the fitted theoretical distribution model is significant on a chosen significance level, α. Here the χ^2-test is applied. The χ^2-test is based on dividing the data into classes and comparing the empirical number of observations, O_i in each class, i with the theoretically expected number, E_i. The test statistic is calculated from the relationship

$$\chi_c^2 = \sum_{i=1}^{m} \frac{(O_i - E_i)^2}{E_i} \tag{2.14}$$

where m is the number of class intervals. The hypothesis that the empirical data comes from the chosen theoretical distribution is rejected if

$$\chi_c^2 > \chi_{1-\alpha,\nu}^2 \tag{2.15}$$

where 1 - α is the confidence level and ν is the degrees of freedom. The number of the degrees of freedom is calculated from the number of classes, m and the number of parameters that have to be estimated, r, which dependents on the kind of theoretical function:

$$\nu = m - r - 1 \tag{2.16}$$

It is commonly recommended to divide the data into at least 6 classes of equal width, whereby each class should still obtain a minimum of 5 events, except for the outer classes which can have less (Haan, 1977).

2.4.1 Frequency analysis for deficit characteristics with NIZOWKA2003

The program NIZOWKA2003 is based on a method presented by Zelenhasić & Salvai (1987) "of completely describing and analyzing the stochastic process of streamflow droughts" (Zelenhasić & Salvai, 1987), when the drought events are selected by the threshold level method. Zelenhasić & Salvai (1987) suggested to derive the cumulative distribution function of the largest streamflow drought occurring in a given time interval from a PDS of drought events. The method works on daily discharge data for drought events lasting less than one year and characterises droughts either in terms of their deficit volume or their duration. It is assumed that streamflow droughts are iid random variables and that their occurrence is subject to the Poisson probability law. As such the method consists of two parts. The first one is to estimate the probability of the number of events occurring during the chosen time interval. The second part is to estimate the distribution function of the chosen deficit characteristic of all drought events occurring in the chosen time interval. From that Zelenhasić & Salvai (1987) calculated the distribution function of the largest drought event within any given time interval [0, t], $F_t(x)$ in the following way:

$$F_t(x) = \Pr(Z_t = 0) + \sum_{k=1}^{\infty} H_t^k(x) \Pr(Z_t = k) \tag{2.17}$$

with: $F_t(x)$ distribution function of the largest drought event (expressed as deficit volume or duration) within any given time interval [0, t]

$\Pr(Z_t = k)$ the probability that k drought events occur during the time interval [0, t], which is a Poissonian process

$H_t(x)$ distribution function of all drought events (expressed as deficit volume or duration) within the time interval [0, t]

When the time interval is set to one year, return periods and T-year events can be estimated according to Equation (2.12).

The theory of the method is based on the assumption that the considered drought events are iid and that they are extreme events. Therefore the theory of the method holds, according to Zelenhasić & Salvai (1987), only for drought series derived using a low threshold level, either $Q95$ or $Q90$. In addition, minor droughts should be excluded. Zelenhasić & Salvai (1987) excluded all minor droughts having a deficit volume smaller than α times the maximum observed deficit volume. They suggested to set α equal to 0.005 or 0.010. In NIZOWKA2003 the α-criteria is offered as well as a second criteria to exclude minor droughts. The second criteria excludes all pooled drought events containing less than a certain number of days, d_{min} of discharge values less than the threshold level, Q_0. Hence, d_{min} does not refer to the total drought duration as defined when introducing the IT-method in Section 2.3.1, but it refers to the actual number of days with $Q(t) < Q_0$. The user can chose to use either one of the two criteria or both at the same time. Higher values of α and d_{min} might have the advantage of really excluding all minor drought events and thereby allowing to increase the accuracy of the estimation of the most extreme events. However, not only minor events could be removed and the number of remaining drought events for the estimation becomes less. If only few events remain, no proper estimation can be accomplished anymore. This risk is especially present when working with data records of short duration.

NIZOWKA2003 offers to fit any of the following distribution models to $\Pr(Z_t = k)$ and $H_t(x)$:

$\Pr(Z_t = k)$: Poisson or Pascal distribution

$H_t(x)$: Gamma/Pearson type 3, Weibull, Log-Normal, Johnson, Double Exponential/Gumbel or Generalized Pareto distribution.

The goodness-of-fit is tested with the χ^2-test described above.

3 Data

3.1 The global data set

The global data set consists of 16 daily discharge series from around the world (Figure 3.1). The periods of record vary from 15 to 99 years. The data set was assembled by the ASTHyDA project trying to demonstrate the variability of hydrological regimes globally through including streams from most of the major climate zones on both hemispheres and with different hydrogeological catchment characteristics. As such the global data set contains catchments from cold regions (e.g. Lågen and Inva), tropical regions (e.g. Honokohau), moist, temperate regions (e.g. Hurunui and Bagamati), dry, arid (e.g. Dawib) and semi-arid (e.g. Arroyo Seco) regions (Rees et al., 2004). In addition three catchments of the same climate region but with different hydrogeological characteristics are included: a permeable catchment (Lambourn, Great Britain), showing a low variability of flows, an impermeable catchment (Ray, Great Britain) with a flashy flow regime, and a catchment with a mixed response to precipitation events (Lindenborg, Denmark). Two series of the ASTHyDA data set were not used for this study: one Spanish river which was added to the ASTHyDA data set after the start of this study and one British river whose flow regime was considered to be too strongly influenced by humane activity in order to be useful.

Figure 3.1 Catchments of the global dataset used in this study (modified from Rees et al., 2004).

In the following section all catchments of the global data set are introduced, grouped by climate regions according to the Köppen climate classification system. For each catchment a brief description of its climate, its catchment characteristics and hydrological regime is given together with a graph of 10 years of daily discharge data. A summary of the characteristics is given in Table 3.1, and the mean monthly discharge values standardised by the mean discharge (*MQ*) are displayed in Figure 3.2. In Appendix 1 graphs of one year of daily discharge data (1980) are presented together with an enlarged version of the 10 year record.

The Köppen climate classification system defines five climate zones on the basis of mean annual and mean monthly temperature as well as mean annual and mean monthly precipitation. The five climate zones are A: Tropical, B: Dry, C: Temperate, D: Cold and E: Polar. They are further subdivided - again with the help of the above mentioned climate characteristics - into eleven climate types (Mühr, 2003 and Stahl & Hisdal, 2004), which are described in more detail together with the introduction of the catchments in the following section. In addition to the Köppen Classification the mean annual precipitation, *AAR* of the catchments is given. Information about the annual cycles of temperature as well as precipitation was often only available as averages over 30 years (climate normals) and for a wider area. Which means that they might not exactly account for the topography of the catchment and usually do not cover the same time period as the discharge records. Despite these inaccuracies, this climate information is still very helpful for the characterisation of the catchments, the understanding of the discharge regimes and especially for pointing out the differences of the 16 catchment areas of this study. So for example one has to keep in mind in general that in the climate zones closer to the equator (A and most regions with a B-climate) the interannual variability of precipitation is higher than the interannual variability of temperature, which makes precipitation the most important climate factor for explaining annual discharge cycles. In the climate zones further south or north of the equator the interannual variability of temperature becomes stronger, allowing only a reduced growing season and affecting the water recharge to streams through the seasonality of evaporation as well as of water demand by plants. In regions with a C- or D-climate the annual discharge cycle is therefore strongly influenced by the annual cycles of precipitation as well as temperature.

The catchments are characterised through their area, the altitude of the station for discharge measurement, the maximum as well as the mean altitude of the catchment and the areal percentage of lakes within the catchment, *LAKE*. Hydrogeological catchment characteristics

Table 3.2 Catchment and discharge characteristics of the streams of the global data set

Stream, Site	**Country**	**Köppen Climate Zone**	**Streamflow type**	**Area (km^2)**	**Station Altitude (m a.m.s.l.)**	**Maximum Altitude (m a.m.s.l.)**	**Mean Altitude (m a.m.s.l.)**	***LAKE* (%)**	***AAR* (mm)**	***BFI* (season)**	***q* ($l/(s \cdot km^2)$)**	**c_{zero} (%)**	***CVd***	***CVa* (season)**
Honokohau Stream, Honokohau	Hawaii, USA	Af	perennial	11	256	ca. 1765[4]		0.0[3]		0.47	98.36		1.23	0.26
Dawib, Dawib	Namibia	BW	ephemeral	560	>200[4]	<2000[4]				0.00	0.02	98.2	14.17	0.87
Pecos River, Pecos	USA	BS	perennial, seasonal	490	2287	ca. 3993[4]	3021	0.1	474-610	0.75	5.92 (7.34)[6]		1.30	0.50
Elandrivierie, Elands River Drift	South Africa	Cw	intermittent	690	1000-1500[4]	poss. >3000[4]				0.26	3.53	3.0	2.44	0.57
Bagamati River, Sundurijal	Nepal	Cw	perennial	17	1600					0.81	62.88		1.02	0.22
Sabar, Alfartanejo	Spain	Cs	intermittent	39	500-1000[4]	1671[4]				0.20	4.54	50.9	3.62	0.68
Arroyo Seco, Soledad	USA	Cs	intermittent	632	103			0.0[3]	802-864	0.42	7.66	12.5	3.35	0.67
Ray, Grendon Underwood	United Kingdom	Cf	intermittent	19	66	187	98	0.5	660	0.17	5.11	26.4	2.76	0.40
Lambourn, Shaw	United Kingdom	Cf	perennial	234	76	261	164		805	0.97	7.25		0.48	0.23
Lindenborg, Lindenborg Bro	Denmark	Cf	perennial	214	5	113	20-40	1[1]	741[1,2]	0.89	10.90		0.35	0.14
Ngaruroro, Kuripapango	New Zealand	Cf	perennial	370	500	1617	979	ca. 0	2000-2150[5]	0.55	46.97		1.06	0.17
Hurunui, Mandamus	New Zealand	Cf	perennial, seasonal	1060	300	1987	976	1.6	1919	0.63	49.79 (45.16)[6]		0.86	0.22
Lågen, Rosten	Norway	Df	perennial, seasonal	1755	737	2200	939	0.7	700	0.68	52.24 (31.26)[6]		0.83	0.30
Inva, Kudymkar	Russia	Df	perennial, seasonal	2050	0-100[4]	200-500[4]	209	0.0	700-800	0.41	6.06 (6.91)[6]		1.87	0.45
Rhine, Lobith	The Netherlands	Df, Cf	perennial, (seasonal)	160800	10	4275			716	0.84 (0.88)[6]	13.74 (13.00)[6]		0.51 (0.46)[6]	0.23 (0.22)[6]
Ostri, Liavatn	Norway	Df, ET	perennial, seasonal	235	733	2088	1410	3.5	1560	0.59	44.69 (98.39)[6]		0.61	0.18

[1] from Ovesen et al. (2000) [2] average for the period 1971-1998 [3] from USGS (2003) [4] from The Times (1994) [5] Clausen, 2003 pers. comm. [6] summer

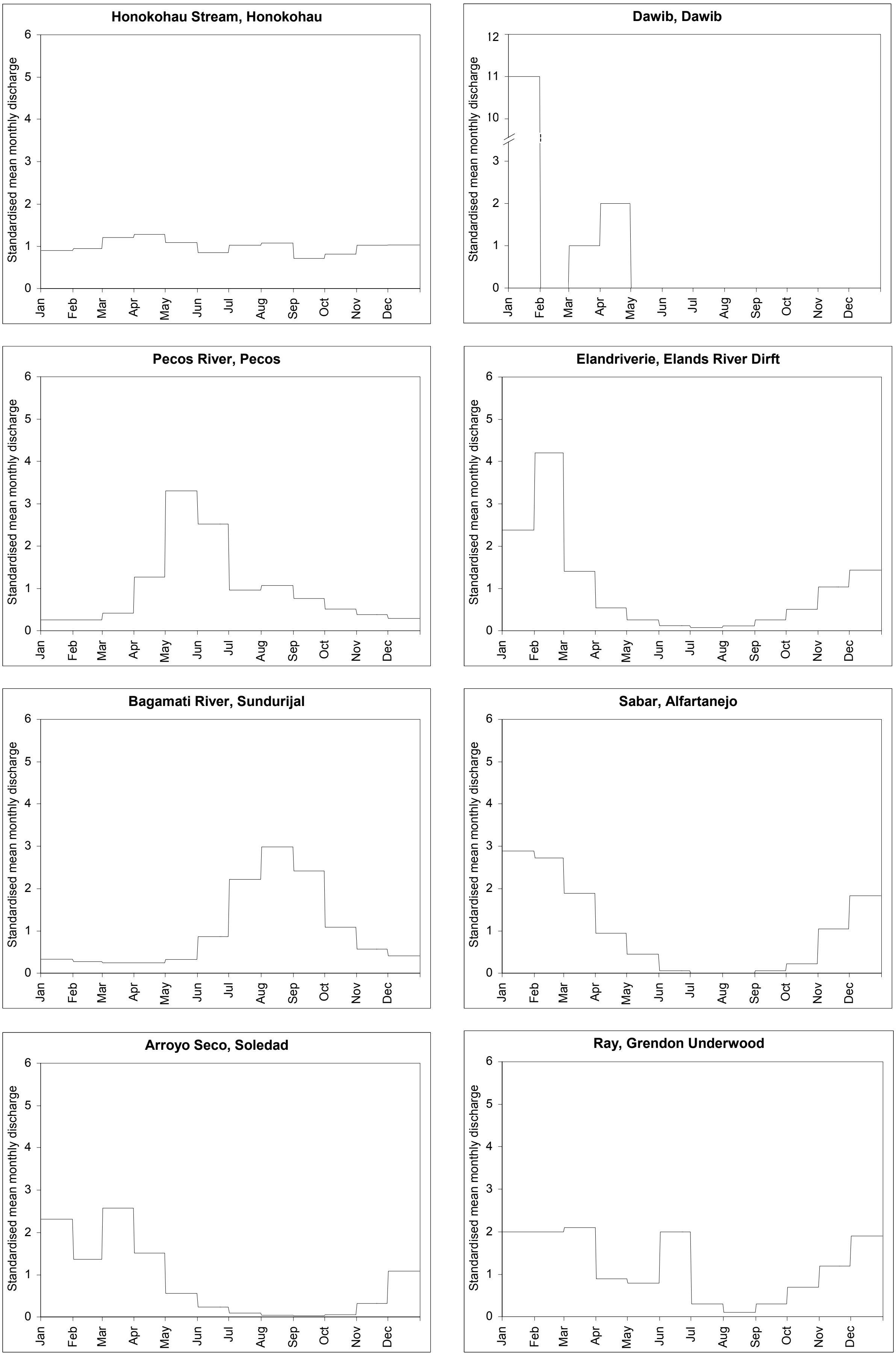


Figure 3.2 Standardised mean monthly discharges for all stations of the global data set.

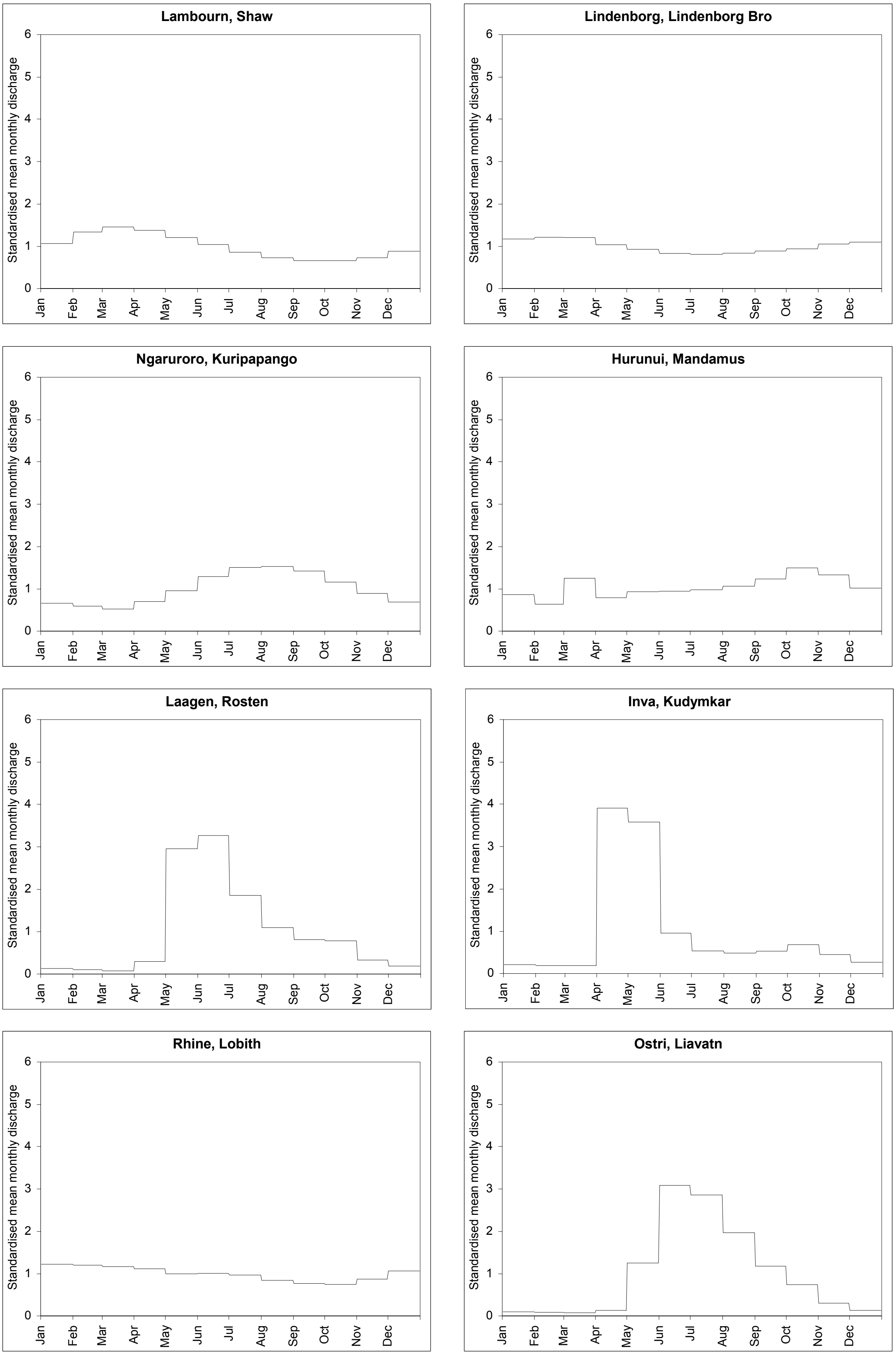


Figure 3.2 (continued).

were in many cases not available and are therefore missing in this description as well as in the summary in Table 3.1.

As discharge characteristics the specific discharge, q from the catchment, the Base Flow Index, *BFI* and the percentage of time with zero discharge, c_{zero} are given as well as the coefficients of variation of daily data series, *CVd* and of the annual data series, *CVa*. The specific discharge is the mean discharge divided by the catchment area. The *BFI* expresses the fraction of runoff derived from stored sources within the total runoff, it is thus an index for the effects of the catchment geology on the discharge (Gustard et al., 1989). The *BFI* is calculated by a sequence of smoothing and separation rules on the mean daily discharge hydrograph, of which a detailed description can be found in Gustard et al. (1989). Values of the *BFI* range from values close to 1 for streams with a permeable catchment and a very stable flow to values between 0.15 and 0.20 for impermeable catchments with a flashy hydrograph and possible some zero-flow periods. In case of a high percentage of zero-flow values the *BFI* is of course as low as 0. The final values of discharge characteristics as presented in Table 3.1 have been calculated from the quality controlled data series as they were used for the calculations of the drought characteristics. And for catchments experiencing a frost season only the discharge data from the summer season is used. More details on quality control and seasonal aspects are given in Section 3.2.

The streams are also classified according to their streamflow type. The streamflow type expresses the consistency in flow, which depends on the hydrological system of its catchment, and the height of the groundwater table relative to the streambed. Streamflow can either be *perennial*, when water in the stream is continuously flowing, *intermittent*, when the flow ceases during the dry season, or *ephemeral*, when flow occurs only directly after a rainfall event. Sometimes confusion exists about how to classify streams, which do not fall dry regularly for a longer period each year during the dry season, but only in some years for several days. Should they be considered to be perennial in spite of their short zero-flow periods, or should they be classified as intermittent streams even though they do not fall dry on a regular basis each year and only for short periods? The following definition is taken from the ‘Handbook of Hydrology’, Chapter ‘Streamflow’ (Mosly & McKerchar, 1993):

“Streamflow may be

a) **perennial**, in a channel which never dries up,

b) **intermittent**, in a channel which at drier times of year may have some reaches with flowing water interspersed with other reaches in which the water flows below the surface,

c) **ephemeral**, in a channel which flows only after rainfall."

It was decided for this study to classify all streams as intermittent, which experience zero-flow at some times and are not ephemeral. The streamflow type of streams experiencing a frost season is additionally marked with 'seasonal', since for the calculations of the drought characteristics only the frost free season is considered.

3.1.1.1 Class Af: Tropical

This is a very warm and humid region with relatively high precipitation and temperature values all year around, only showing little inter-annual variation, especially in temperature values, but relatively high precipitation and temperature differences according to altitude. Rain events are usually caused by convection and therefore they are quite strong and occur frequently throughout the year. The climate normals from 1971-2000 show that at low altitudes precipitation is highest from November till April and lower from May till October. At higher altitudes there is a second precipitation maximum in July and August (Golden Gate Weather Service, 2003).

Honokohau Stream at Honokohau, Hawaii, USA

The catchment of Honokohau Stream spans over a wide altitude range from 256 m a.m.s.l. to 1765 m a.m.s.l. and the monthly discharge averages show two maxima. The primary minimum is in September and October and the primary maximum in March and April.

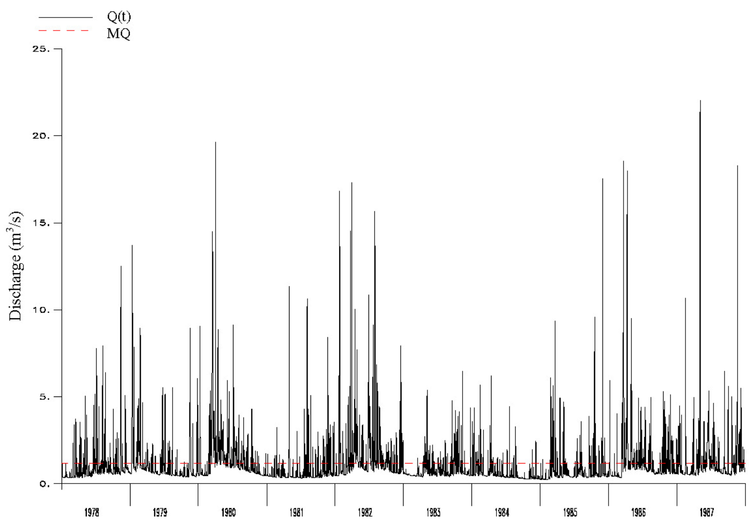


Figure 3.3 Daily discharge from 1978-1987 for Honokohau Stream at Honokohau, Hawaii.

According to the climate of this region the daily discharge hydrograph of Honokohau Stream is in general very flashy with a high mean specific discharge of q = 98.364 l/(s·km^2) caused by the frequent strong rain events and the discharge is approximately derived equally from stored sources and fast runoff with a *BFI* equal to 0.47.

3.1.1.2 Class BW: Dry – desert

The desert climate is characterised by a permanent negative water balance, meaning that evapotranspiration amounts exceed precipitation during the whole year. Rain events occur only a few times per year or not at all, each event lasting only for a couple of days.

Dawib at Dawib, Namibia

Dawib is ephemeral and has water only a few days per year. The flow events occur during or slightly after a rain event, most often during the months January till March. In some years the streambed stays dry for the whole year.

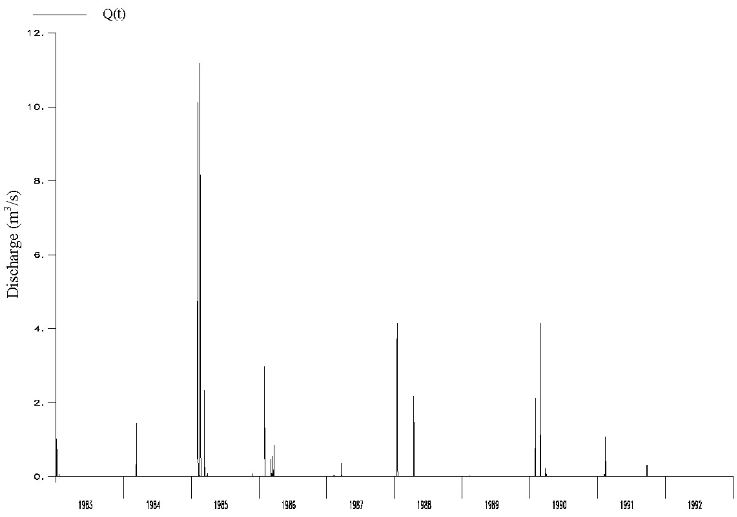


Figure 3.4 Daily discharge from 1983-1992 for Dawib at Dawib, Namibia.

3.1.1.3 Class BS: Dry – steppe

In this region the annual evaporation also exceeds the annual precipitation, but the year consists of a dry as well as a wet season and therefore the negative water balance is not consistent throughout the year.

Pecos River at Pecos, New Mexico, USA

The Pecos River experiences a dry season during the winter months, lasting from November to April and a wet season from May to October with the highest monthly precipitation amounts in July and August (WRCC, 2003).

The catchment area of Pecos River is located at a relatively high altitude (station altitude: 2287 m a.m.s.l. and maximum altitude: ca. 3993 m a.m.s.l.) and in the winter precipitation falls as snow. Usually snowmelt occurs slightly before and then overlaps with the beginning of the wet season, together resulting in a distinct discharge peak in the regime of Pecos River during Mai and June.

Even though it lies in a dry region and has a relatively low mean specific discharge of 5.919 l/(s·km^2) Pecos River is a perennial river, never experiencing zero flows, probably due a permeable catchment with a good storage capacity, which is also expressed in a relatively high *BFI* of 0.75.

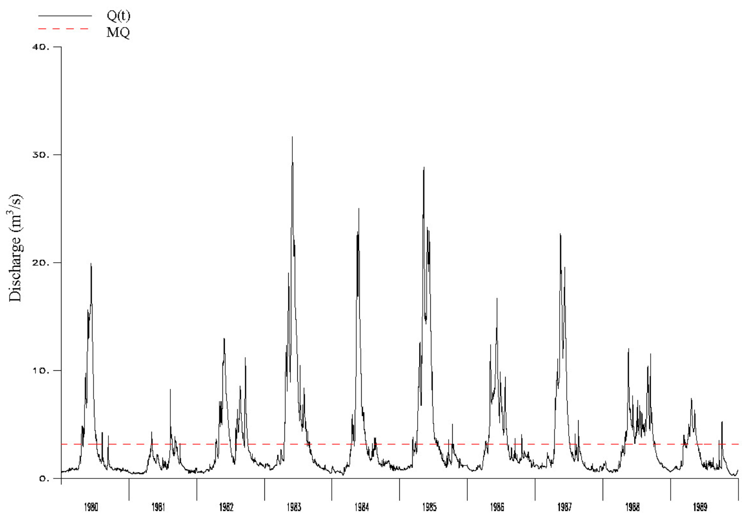


Figure 3.5 Daily discharge from 1980-1989 for Pecos River at Pecos, USA.

3.1.1.4 Class Cw: Temperate – winter dry

This climate is characterised by a distinct annual cycle of temperature, resulting in winter and summer seasons. Precipitation is relatively low during the winter and high during the summer. The mean annual precipitation amount varies considerably between regions within the Cw climate zone from less than 200 mm/a to more than 10000 mm/a in the monsoon influenced regions. In most regions it can also happen that in some months during the winter it does not rain at all (Mühr 2002).

Elandriverie at Elands River Drift, South Africa

The mean annual precipitation probably lies around 500 mm/a, estimated from the precipitation normals of surrounding stations given in Mühr (2003), and the lowest mean monthly precipitation values are found in the winter months from May till September. Mean monthly temperature values are never less than 5 °C and not much higher than 25 °C (Mühr, 2003).

The mean monthly discharge values of Elandriverie show a minimum from April till August and a maximum in February. The mean specific discharge is 3.527 l/(s·km^2). Baseflow contributes only little to the total discharge of Elandriverie (BFI = 0.26) and the river sometimes falls dry during the winter and shows a low discharge for longer periods. But also during the relatively seen wet season the river experiences shorter periods of low discharge and also some zero-flow days. In total Elandriverie shows zero-flow in 3 % of the time.

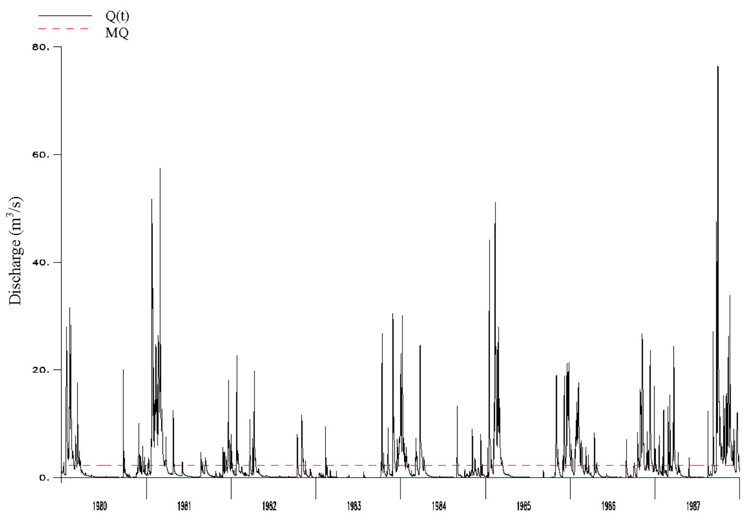


Figure 3.6 Daily discharge from 1980-1989 for Elands River at Elands River Drift, South Africa.

Bagamati River at Sundurijal, Nepal

For the catchment area of Bagamati River no precipitation data are available and it is difficult to estimate it from data of neighbouring areas, since in the mountainous region of Nepal precipitation amounts depend very much on the precise geographical and topographical location of the area which determine the extend of the monsoon influence. But the mean precipitation distribution over the year is everywhere the same: very small precipitation amounts fall from November till March/April and comparatively very high amounts from June till September. In some regions close to the Bagamati catchment area the maximum of the mean monthly precipitation amounts is only slightly more than 100 mm/month whereas in other regions close by it can be as much as 3300 mm/month (Mühr, 2003).

In accordance with the precipitation regime the mean monthly discharge values of Bagamati River are also very low from November till May and more than seven times as high in July, August and September. Baseflow is calculated to account for 80.51 % of the total discharge. Despite the low discharge during the winter months the mean specific discharge is still high, being 62.882 l/(s·km^2).

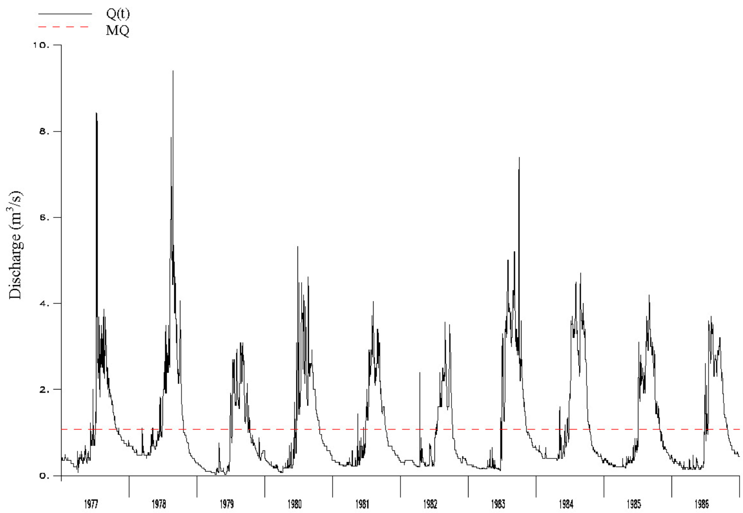


Figure 3.7 Daily discharge from 1977-1986 for Bagamati River at Sundurijal, Nepal.

3.1.1.5 Class Cs: Temperate – summer dry

The Cs-climate has mostly the same features as the Cw-climate except that the dry period occurs in the summer and the wet period in the winter.

Sabar at Alfartanejo, Spain

The catchment area of the river Sabar experiences a dry season lasting from May to September and a wet season from October to April. And Sabar has long zero-flow periods in the summer months (June to September) and continuous flow during the winter months. Totally, it has zero-flow in 50.6 % of the time. During the wet season the river is fast responding to rain events also with a quick decrease in discharge after a rain event. It has a low *BFI* of 0.20 and a relatively high annual variability: *CVa* = 0.68. Sabar also has a low mean specific discharge of 4.540 l/(s·km^2).

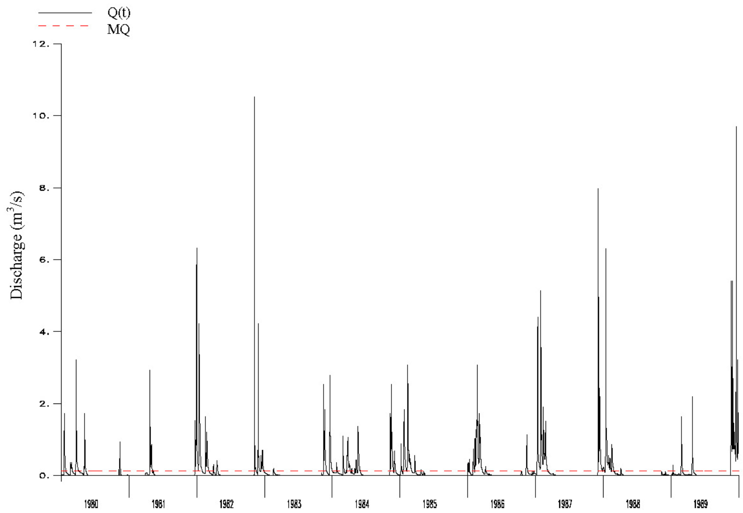


Figure 3.8 Daily discharge from 1980-1989 for Sabar at Alfartanejo, Spain.

Arroyo Seco at Soledad, USA

Mean annual precipitation amounts vary considerably within the catchment area of Arroyo Seco, from 250 mm in the valley to 1500 mm/a in some of the mountainous parts. The average over the whole catchment area is a slightly more than 800 mm/a. Most of the precipitation falls during the winter, from November to March (MCWRA, 2003).

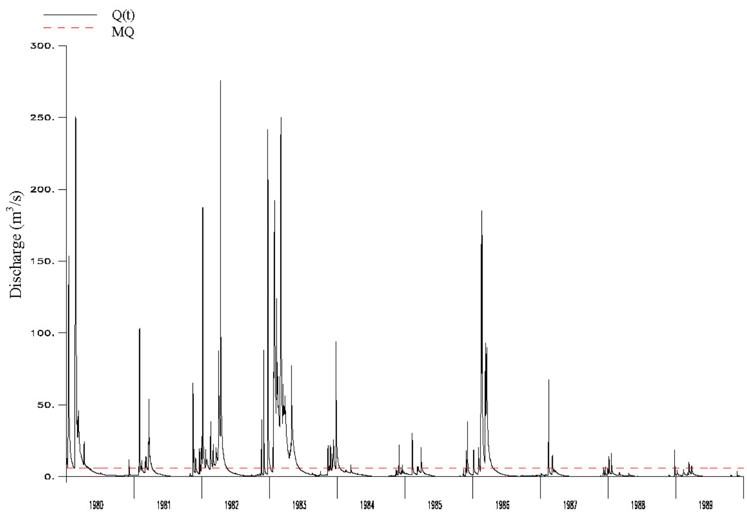


Figure 3.9 Daily discharge from 1980 to 1989 for Arroyo Seco at Soledad, USA.

The mean monthly discharges of Arroyo Seco are very low from May till November and show a peak in February. During the dry summer months the river often falls dry, sometimes even continuously for several months, while in other years it does not fall dry at all. On average it is dry during 12.5 % of the time. Also the annual variation of total annual discharge volume is high with an *CVa* of 0.67. This can also be seen from the hydrograph in Figure 3.9, which shows the mean daily discharge from 1980 to 1989. Despite the long zero flow periods Arroyo Seco has a mean specific discharge of 7.663 l/(s·km^2). According to the *BFI* baseflow accounts for 42 % of the rivers discharge.

3.1.1.6 Class Cf: Temperate – no dry season

The Cf-climate is also characterised by a distinct annual cycle of temperature, resulting in a winter and a summer season and similar temperature ranges as in the Cw-climate, but here precipitation occurs during the whole year. Throughout the year precipitation is mostly caused by eastwards migrating anticyclones, which leads to no distinct dry season, while a precipitation maximum still occurs during the winter months. For the three catchments on the northern hemisphere (Ray, Lambourn, Lindenborg) this maximum is extended into the autumn and lasts from September to December while a clear minimum occurs during the spring (Frich et al., 1997 and Mühr, 2003). For the two catchments on the southern hemisphere, both in New Zealand, the precipitation maximum lasts from May to August which is the winter and early spring on the southern hemisphere (Metservice, 2003). The two New Zealand catchments also belong to a mountain range which receives high amounts of mean annual precipitation (around 2000 mm), much more than the three catchments of the northern hemisphere. There the mean annual precipitation lies around 650 – 800 mm.

Ray at Grendon Underwood, Great Britain

The catchment area of Ray is relatively flat and small (station altitude: 66 m a.m.s.l., maximum altitude: 187 m a.m.s.l and area: 19 km^2). The soils consist mostly of an impermeable Oxford Clay, which causes it to respond very fast to rain events and to even fall dry several times each year. This is clearly visible in the flashiness of the stream's hydrograph in Figure 3.10 and expressed in the low *BFI* of 0.16. The discharge regime is further characterised by a long minimum during the summer and a long maximum during the winter, caused by the temperature maximum and maximum of water demand during the summer and the precipitation maximum during the winter, combined with the low amount of baseflow contributing to the stream.

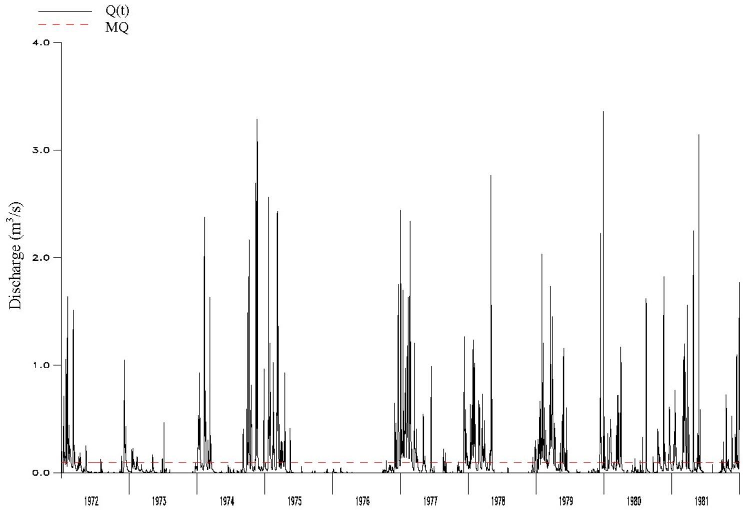


Figure 3.10 Daily discharge from 1972-1981 for Ray at Grendon Underwood, UK.

Lambourn at Shaw, Great Britain

The catchment of Lambourn lies in the same climate region as that of Ray and has a similar mean specific discharge (Ray: 5.11 l/(s·km^2), Lambourn: 7.25 l/(s·km^2)), but it is very permeable and baseflow accounts for almost all of the river's discharge (*BFI* = 0.97). As such the annual cycle generated by the climate and shifted through retention in the catchment is clearly visible in its hydrograph, only slightly superposed by daily variability. It also shows a comparatively low annual variability with *CVa* = 0.23. The maximum of the discharge regime lies in February until April and the minimum in August until November.

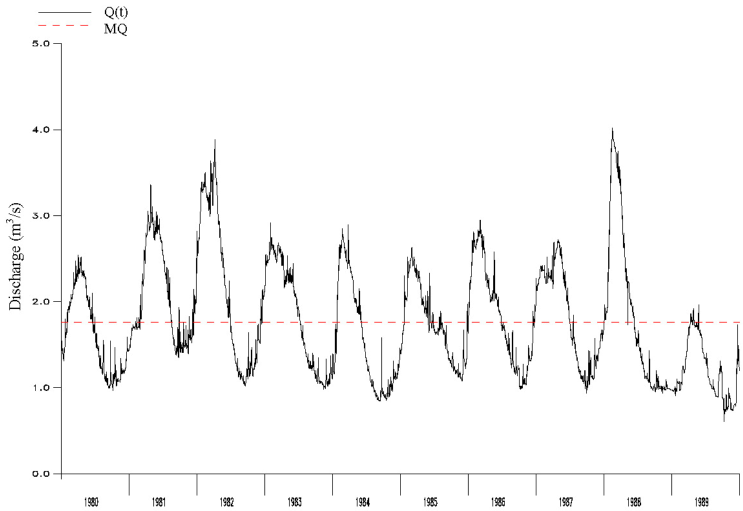


Figure 3.11 Daily discharge from 1980-1989 for Lambourn at Shaw, UK.

Lindenborg at Lindenborg Bro, Denmark

Lindenborg also belongs to the same climate region as the two British rivers Ray and Lambourn, but its respond to rain events is mixed, its discharge experiencing a higher contribution from direct runoff as it is the case for Lambourn. This is expressed in the lower *BFI* of 0.89 and also in the smaller shift of the annual maximum and minimum in the discharge regime compared to the annual cycle of temperature and water demand. Lindenborg has its maximal discharge in January until March and the minimal discharge in June until September, its mean specific discharge is q = 10.90 l/(s·km^2).

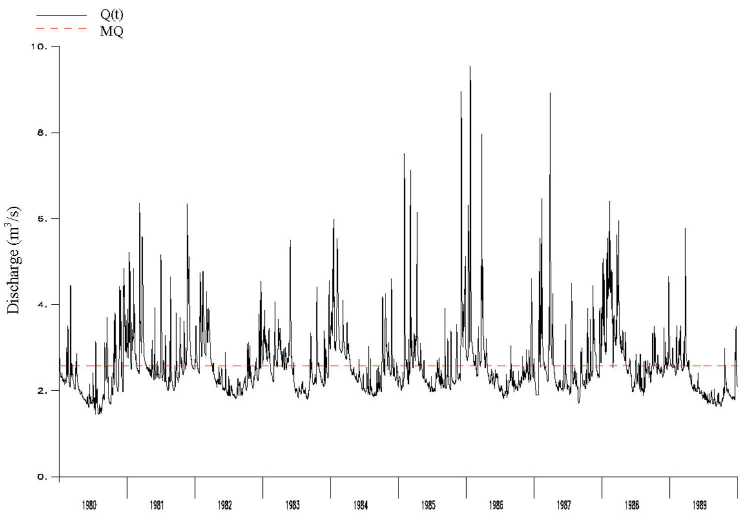


Figure 3.12Daily discharge from 1980-1989 for Lindenborg at Lindenborg Bro, Denmark.

Ngaruroro at Kuripapango, New Zealand

The catchment of Ngaruroro is mostly covered with forest, a small part of the catchment lying above the timber line (Clausen, 2003 pers. comm.). In a temperate climate forest usually prevents huge amounts of direct runoff from the catchment. Ngaruroro has a *BFI* of 0.56, which indicates that almost half of the rivers discharge amount comes from fast runoff. This is probably because of the humid conditions in this area, which could cause the soils to be saturated most of the time and thereby causing relatively large amounts of fast runoff. It can also be seen from the discharge hydrograph in Figure 3.13 that this river responds quite fast to rain events. The mean monthly discharges are the highest during the winter (June until September) and the lowest during the summer (December until April). Compared to the catchments in Great Britain and Denmark the higher mean annual precipitation results in a much higher mean specific discharge of 46.97 l/(s·km^2).

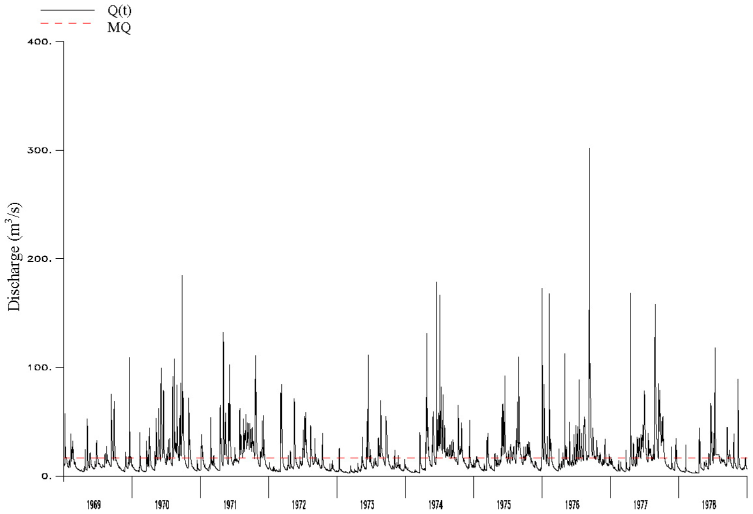


Figure 3.13 Daily discharge from 1980-1989 for Ngaruroro at Kuripapango, New Zealand.

Hurunui at Mandamus, New Zealand

The catchment of Hurunui lays in the same mountain range as that one of Ngaruroro, but it spans a wider altitude range and reaches higher up (Hurunui: Station Altitude = 300 m a.m.s.l. and Maximum Altitude = 1987 m a.m.s.l., Ngaruroro: Station Altitude = 500 m a.m.s.l. and Maximum Altitude = 1617 m a.m.s.l.). In the winter months the catchment is partly snow covered. Since it still receives rain in other parts of the catchment, the mean monthly discharges are not at a minimum in the winter, but the discharges from June till September are lower compared to those of Ngaruroro. The maximum is shortened and delayed until October and November when the melting of the snow occurs together with high precipitation amounts.

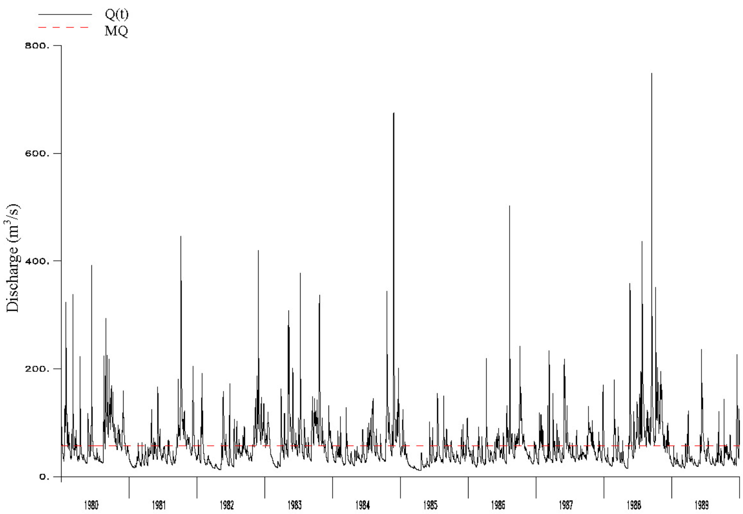


Figure 3.14 Daily discharge from 1980-1989 for Hurunui at Mandamus, New Zealand.

Other characteristics, such as the relatively high mean specific discharge (49.790 l/(s·km^2)), a fast respond to rainfall events and the *BFI* (0.63) are similar to those of Ngaruroro.

3.1.1.7 Class Df: Cold – no dry season

The average temperature of the warmest month in the cold climate region is > 10 °C and that of the coldest month is < -3 °C. Precipitation occurs all year around with at least 30 mm in the driest month and little difference between the driest and the wettest months compared to other climate regions. Mean monthly precipitation is the highest from June to October. In the winter months precipitation falls as snow and does not contribute to the discharge of a stream until the snowmelt in spring or early summer. Then it might cause high discharge peaks and even serious flood events. Some rivers in these regions freeze completely during some time in the winter or they freeze over on the surface. When precipitation and water in the catchment get stored in form of snow and ice, streams experience a continuous low flow period in the winter.

Lågen at Rosten, Norway

The Lågen catchment in Norway is with the exception of the Rhine catchment one of the larger ones considered in this study (Area = 1755 km^2). 73 % of its area lay above the timber line. The whole catchment lies within the same climate region, but it experiences a large precipitation gradient within the catchment. The mean annual precipitation varies from 400 to 1500 mm. Usually, more precipitation falls during the summer than during the winter months.

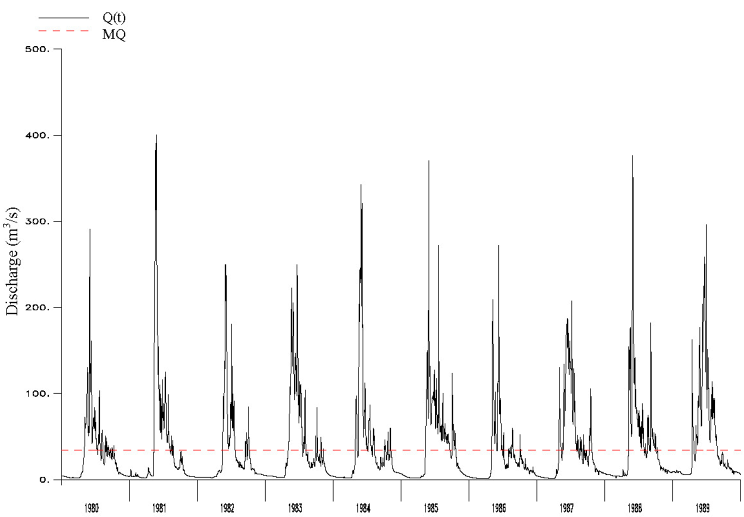


Figure 3.15 Daily discharge from 1980-1989 for Lågen at Rosten, Norway.

The mean monthly temperature for the whole catchment is below zero from November till April, but also varies locally according to altitude. The snowmelt starts in May and causes high mean monthly discharge values in May and June. In the hydrograph of daily discharge values from 1980 till 1989 the snowmelt peak can easily been seen (Figure 3.15). A secondary peak often occurs in late summer or early autumn, caused by autumn storms. During the period June 15th to September 30th Lågen has a relatively high *BFI* of 0.63 and a specific discharge of $q_S = 31.26$ l/(s·km^2). For the whole year q is somewhat higher with $q = 52.24$ l/(s·km^2).

Inva at Kudymkar, Russia

The areal extension of the Inva catchment is somewhat larger than that of the Lågen catchment in Norway. However, the catchment of Inva is relatively flat and does not experience the same precipitation gradient as the Lågen catchment. It also receives less precipitation during the winter than during the summer months. The average precipitation amount for the cold period from November till March is 250 - 300 mm, whereas the average for the warm period is around 500 mm. A stable snow-cover is on average present from November until the end of April when the snowmelt begins. The river freezes on average for 170 days per year. The onset and duration of the snowmelt period show little variation from year to year. Even though the mean annual as well as the mean seasonal precipitation amounts are similar to those of the Lågen catchment, the duration of the snowmelt flood is much shorter for the Inva catchment. This is a result of the much smaller altitude range, which does not cause big temperature differences within the catchment and therefore the snow of the whole area melts at approximately the same time.

Despite the precipitation maximum during the summer the snowmelt peak a clearly pronounced peak in the plot of the mean monthly discharge values, occurring during April and May (Figure 3.2). Within the summer season a small maximum is apparent in October, possibly caused by autumn storms. Inva has a specific discharge of $q = 6.06$ l/(s·km^2) as average for the whole year, which is only slightly different to the specific discharge during the summer period May 1st until October 31st of $q_S = 6.91$ l/(s·km^2). The *BFI* during the summer period is 0.41.

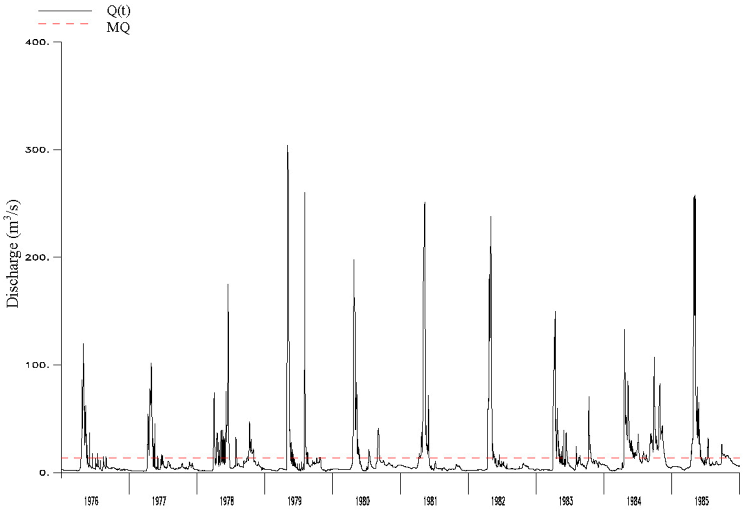


Figure 3.16 Daily discharge from 1976-1985 for Inva at Kudymkar, Russia.

3.1.1.8 Classes Cf and Df

Rhine at Lobith, the Netherlands

The Rhine is a major stream in western Europe, having a catchment area of 160 800 km^2 and a mean discharge of 2210 m^3/s at the station Lobith on the Dutch-German border. Its catchment area covers parts of several countries as well as several climate regions caused by different altitudes from the high Alps in the south of its catchment area, over low mountain ranges to the lowlands in the north. The maximum catchment altitude is 4275 m a.m.s.l., whereas the station lies at an altitude of only 10 m a.m.s.l. The climate in the Alps can be classified as a cold Df-climate and the rest of the catchment experiences a temperate Cf-climate. So in all parts of the catchment area no distinct dry season exists but almost everywhere summer precipitation is higher than winter precipitation. In the Alps as well as in the low mountain ranges mean monthly temperature values are below the freezing point for several months during the winter and precipitation and water in these parts of the catchment are stored in form of snow and ice. In the high Alps this frost period is of course much longer than in the low mountain ranges. In the lower parts of the catchment precipitation falls as rain throughout the whole year with the exception of a few days each year.

As a result the fractions of the total discharge volume coming from a specific part of the catchment vary considerably over the year. For example the Alps contribute during the summer with its stored winter precipitation with more than 70 % to the total discharge of the Rhine at Lobith and during the winter months with only 30 %. A clear discharge minimum is found in September and October and a long maximum during the winter, when evapotranspiration values are low. In some years when the winter is dry and cold low flow periods also occur in January and February. The specific discharge of the summer season is with q_S = 13.00 l/(s.km2) only slightly smaller than the specific discharge of the whole year, q = 13.74 l/(s.km2). Of course also soils and geology vary considerably throughout the catchment. For the Rhine at Lobith the BFI is equal to 0.46 for the summer period and again only slightly higher for the whole year with BFI = 0.51.

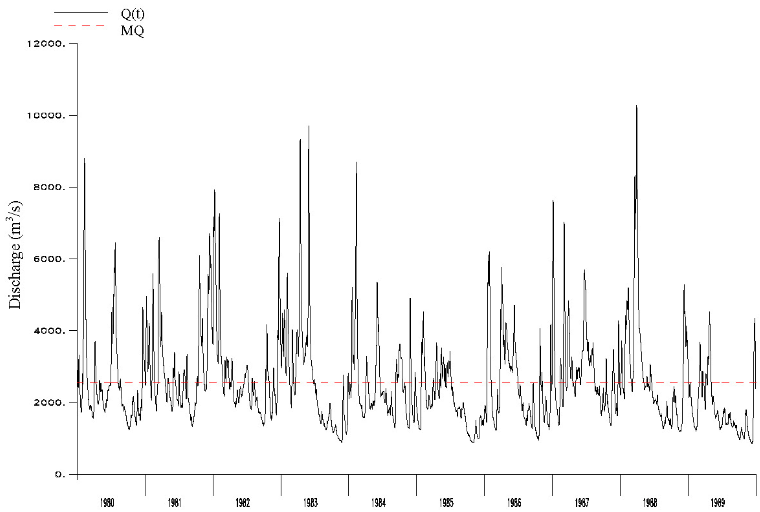


Figure 3.17 Daily discharge from 1980-1989 for Rhine at Lobith, the Netherlands.

3.1.1.9 Classes Df and ET

Ostri at Liavatn, Norway

Parts of the Ostri catchment belong to the ET-climate, which is the polar climate of a tundra region with an average temperature of the warmest month being < 10 °C and > 0 °C. Its altitudes range from 733 m to 2088 m on a catchment area of only 235 km^2. This covers approximately the same altitude range as the other Norwegian catchment, the one of the river Lågen but with a much smaller areal extension. About 12 % of the catchment area is covered with glaciers and the rest of the catchment is snow covered for several months during the winter. The mean monthly temperatures as averages for the whole catchment are below 0 °C from October to May. In the lower parts of the catchment snowmelt starts in May and the major discharge contribution from snowmelt comes in June and July. From the glaciers melting occurs throughout the whole summer, as long as the temperatures are above the freezing point and in some years the meltwater contribution can be higher than the total winter precipitation and in others it can be less. In contrast to the other catchments high temperatures in the Ostri catchment during the summer cause higher discharge values through faster melting rates of glacier ice. Therefore mean monthly discharge values are relatively seen high throughout the summer compared to the mean monthly discharge values of Lågen (Figure 3.2). The mean specific discharge of Ostri is during the summer season (June 15th – September 30th) with $q_S = 98.39$ l/(s·km²) much higher than for the whole year with $q = 44.69$ l/(s·km²). The *BFI* of the summer season is *BFI* = 0.59.

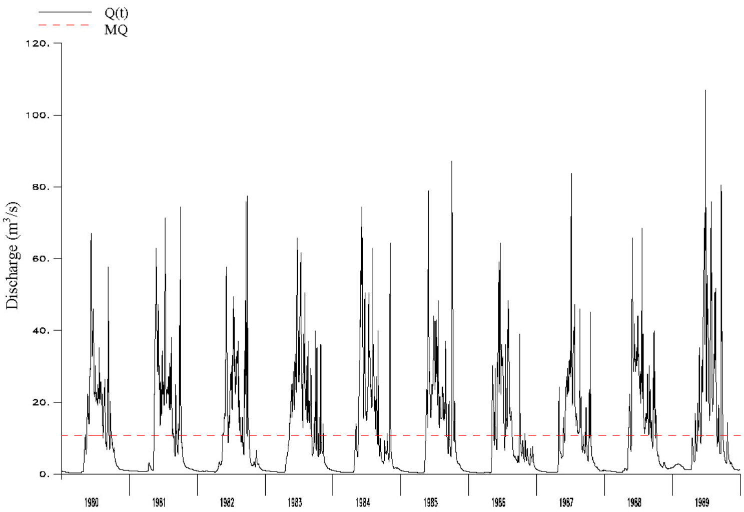


Figure 3.18 Daily discharge from 1980-1989 for Ostri at Liavatn, Norway.

3.2 Data considerations

The data from the global data set are in this section evaluated based on their suitability for drought analysis. This includes two main aspects: (1) the quality of the data and (2) properties of the time series, such as trends and seasonality. Both aspects are described here in a quite detailed way, since some of the data considerations might only be necessary or correct when studying droughts or low flow periods, and others might depend on the regions studied. For a comparable study one has in addition to make sure that all used data series have been treated in the same way and that the chosen series are really comparable. The most basic example would be that they all should be in the same unit and averaged over the same time interval. Here all data is daily data in m³/s.

3.2.1 Quality control

To receive a correct and appropriate data series a proper quality control includes checks for the length of time series, accuracy and continuity and it starts with looking at the processes of measuring and collecting the data (Mosley & McKerchar, 1993). For the data series used in this study little information about the collection and any possibly done pre-processing of the data was available, since the series were assembled from many different sources for the ASTHyDA project. Inaccuracies and problems in the data can be caused in an endless number of ways and they are not always as easily identifiable as barely missing data. It could be human mistakes when measuring or processing the data, the measuring device itself could cause problems or there could be reasons in nature which can lead to wrong conclusions if they are unknown. For example there could be a debris or log jam causing low flow downstream which might be interpreted as low flow caused by a lack of precipitation, or there could be weed growth in the stream influencing the discharge measurements during the summer months as it happens in the river Lindenborg in Denmark. These problems can be hard to identify, unless detailed information about the measurement procedures are available. In such a situation quality control could be based on a comparison with precipitation series or with quality controlled discharge series from neighbouring stations. But also this kind of data is not available for the global data set. In this case a good tool for identifying inconsistencies in the data series is the method of exploratory data analysis (EDA), which at the same time is also a good tool for getting to know the data (Kundzewicz & Robson, 2000). The results from the quality control as well as possibly made corrections for each single river are presented in Appendix 2. In addition to EDA periods with missing data were identified.

3.2.1.1 Exploratory data analysis

EDA is an iterative process which involves using graphs to explore, understand and present data (Grubb & Robson, 2000). Data and results are looked at and visually examined at all steps of an analysis. At each step it its tried to make sure that a complete picture of the data is received and that its important features are revealed by plotting the data in several ways, for example graphing it on different scales (e.g. normal or log scale) or different time resolutions. According to Grubb & Robson (2000) "a well-conducted EDA is such a powerful tool that it can sometimes eliminate the need for a formal statistical analysis." At this point of the study EDA was applied to identify temporal patterns, seasonal variation and data problems. Later on, it was also used to examine the statistical distribution of data values. Plots displaying one year and ten years of all of the daily discharge series are presented in Appendix 1 and plots of the mean monthly discharges in Figure 3.2.

First the major temporal variabilities of the data series were identified by plotting the series on a daily, a monthly as well as on an annual basis and the results were included in the descriptions of the time series in Section 3.1. The next step was to identify data problems such as missing values, sudden jumps in the series and unusually long periods showing a constant discharge. The problems found in each of the time series as well as the handling of those are listed in Appendix 2. Here the identification and handling of the data problems is described in general. Corrections were made as follows:

a) Single data problems, lasting up to 15 days, were removed by taking away the incorrect values and using interpolated values instead.
b) Longer incorrect periods were removed by excluding a whole year of data.
c) Frequent and extensive incorrect periods occurring only in a part of a time series were removed by excluding the whole period from the start of the available time series to the last year with incorrect periods or from the first year with incorrect periods to the end of the time series respectively.

It was necessary to allow also the second option, excluding a whole year of data within a continuously used period of record, since it was considered to ensure a more correct drought study than interpolating over more than 15 days and to still include more data and thereby more information than excluding longer parts of the data series. Interpolating for more than 15 days was considered problematic, particularly, when the interpolated values belonged to a low flow period or when a data series contained many data problems which are in total unevenly distributed over the year. When taking away a whole year of data, the year was chosen in a way that it started and ended within the season in which a discontinuity would not affect the low flow and drought period. In most cases this would be the high flow or the winter season. In some data series several single years of data had to be excluded. In this case the assumption that the same number of wet and try years are left away has to be made. Hence, the choice of how to exclude periods of incorrect data depended on the lengths and frequencies of the incorrect periods as well as on the remaining lengths of continuous correct data.

Missing values

Missing values influence a data analysis since they reduce the length of the data record and since the distribution of the remaining recorded values might deviate from the distribution of the entity of the original values. Some of the methods to derive streamflow drought characteristics also cannot cope with missing values. Since the only available method to fill in the missing values was interpolation, it was decided to include only periods with maximal 15 continuous days of missing values. Not only the duration of periods with missing values was considered, but also which season or section of the regime they belong to and how the total set of gaps for one series is distributed over the year. For some of the rivers the maximal number of 15 days for interpolation was reduced according to the characteristics of their regimes. For example for Dawib, South Africa, many periods of missing data were found, including many shorter ones which lasted only a couple of days. But Dawib is ephemeral and has zero flow most of the time and occasionally, short flow events lasting between one and seven days. Even years without any flow events occur. Most of the recorded flow events occur during January to March, two minor ones in April and one minor event each in September and December. The missing periods belong all to the months December to April. So it is likely that at least in some of the cases the measuring device got set out of function by a flow event. Through interpolation however, all the missing values would be assumed to be zero. Therefore it was decided to not include any periods nor even single days of missing values in the used time series of Dawib. In the case of Dawib it is questionable in general how representative the recorded data are, since a relatively high percentage of the data is missing: 3.94 %. This is higher than the observed 1.8 % of days with flow in the five years of continuous record. Since Dawib has no season with continuous streamflow every year, the option of excluding whole years of data and using all the complete years was rejected.

Periods of constant discharge

Longer periods showing a constant value are frequently observed and can be caused for example by not properly functioning measuring devices or by an earlier conducted interpolation of missing data. During a low flow period, stream flow can also naturally be relatively constant for a longer time period, which can be enhanced through a low resolution of the measuring device. This is however not an error in the data. Therefore, if no information was available about what has caused these periods of a constant value, they are mentioned in the table in Appendix 2 but not excluded from the period of record.

Sudden drop downs or peaks

Single values causing sudden drop downs or peaks which were inconsistent with the rest of the data series were removed and it was interpolated instead.

3.2.1.2 Lengths of data series

A data series contains more information the longer it is, and a minimum length is required in order to cover the natural variability of the series and to provide sufficient data for an analysis. On the other hand, longer data series might show an important significant long-term trend, which often complicates an analysis considerably, as discussed in Section 3.2.2.1. If one is interested in the more recent situation of a stream, a very long data series might not give a correct picture of the recent situation.

For many of the catchments only relatively short data series were available after the quality control, so that all available data should be used.

3.2.2 Data properties

3.2.2.1 Stationarity

Slow changes can complicate an analysis considerably, no matter whether they are a naturally occurring trend or actually an error in the data. For example when the threshold level method is applied on a daily discharge series showing a positive trend, the conclusion would be that many severe and long droughts occurred in the beginning of the observed period and only very few and small droughts in the end of the series (Figure 3.19). But depending on the reason for the trend this might not be the correct description of a natural stream's drought situation, and also no proper frequency analysis of drought characteristics would be possible. It is therefore important to know about a trend in a time series to avoid any wrong conclusions or interpretations.

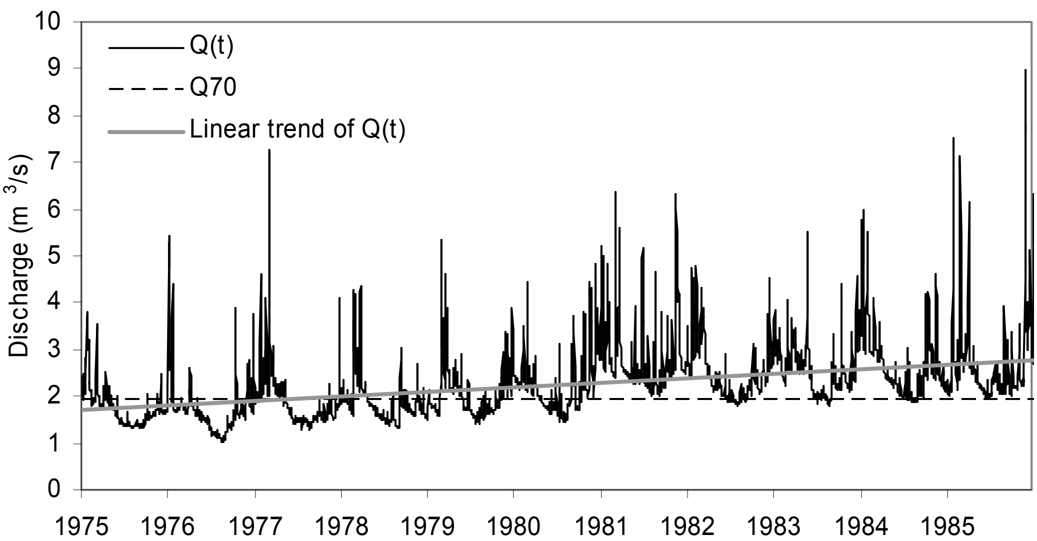


Figure 3.19 Illustration of the influence of a trend on the derivation of a drought series.

A general problem with trend calculations is that they are very sensitive to the length of a data series, and, as Hisdal et al. (2002) point out, to the time period covered by the data series, i.e. when the period starts and ends. As wet and dry years tend to cluster, a trend might be calculated if a series starts with a sequence of wet years and ends with a sequence of try years (or vice versa). These trends are not real long-term trends, but instead caused by the natural variability of the discharge series and the chosen time period. A slightly different or longer period could show a different trend for the same stream. When the record length of a data series is short, it is difficult to determine the real nature of a calculated trend. This is the case for several of the series from the global data set, five of which have a continuous record of less than 30 years.

A seasonal trend, meaning that for example a trend towards lower discharges in the summer and higher in the winter, may result in a trend-free mean annual discharge series. According to Smakhtin (2001), several studies have been conducted evidencing that climate change has different effects on low flows than on high flows and that the effects can even vary within one catchment area, resulting in varying discharge changes along one stream. The latter was reported by Liebscher for the River Rhine in 1983, using a data series starting in the early nineteenth century (Smakhtin, 2001).

Seasonal trends caused by climate changes are especially a problem when seasonal drought studies are to be conducted, as it is necessary in snow influenced regions. A climate change could imply a longer snow free period, suggesting that fixed seasons as discussed in Section 3.2.2.2 are not appropriate anymore. Also for non-seasonal drought studies climate changes can violate the assumption of identically and independently distributed drought events in a frequency analysis. When the weather systems that cause drought events change over the period of record, it is not ensured anymore that the observed drought events are identically distributed.

To reveal non-seasonal as well as seasonal trends in the series of the global data set, the trends were calculated for the series of mean annual discharge, annual daily minimum discharge as well as of monthly mean discharges. The significances of the trends were tested with the non-seasonal Mann-Kendall-Test. In addition to the significance of a trend also its importance has to be evaluated, since a highly significant trend can be so small that it causes almost no change in the data and that it is therefore of no importance (Robson et al., 2000). None of the series in the global data set showed an important significant trend, neither non-seasonal nor seasonal on a significance level of 0.05. But for most streams the trends in monthly mean discharge were slightly higher than for the mean annual discharge.

3.2.2.2 Seasonal aspects

Streamflow droughts can be caused by different climate features and two major types of streamflow droughts can be distinguished: (1) *Summer droughts* which are caused by low precipitation amounts, often accompanied with high temperature and high evapotranspiration, (2) *winter droughts* which occur when the temperature is below the freezing point of water and precipitation and water in the catchment are stored in form of snow and ice in stead of flowing into the stream. Also a series of only summer droughts can contain seasonality, when the weather systems that cause droughts vary over the year, for example in a region with a wet and a dry season. If droughts are of different origin, it has to be decided whether drought characteristics should be calculated for each type separately or whether it is acceptable to derive a mixed series of drought events. If the droughts are to be separated, three aspects are to be considered: (1) the specification of the seasons, (2) deciding whether the threshold level should be based on all-year or on seasonal data, (3) each drought event has to be identified and a series of one type of events is to be selected.

1. Frost season in cold and temperate climates

In the case of summer and winter droughts, there is not only seasonality in the weather systems causing the drought events, but as a consequence also the processes within the catchment differ. Winter droughts are often not considered to be so problematic, since they occur during a time of low natural water demands and the water supply is only postponed but not prevented. For comparable drought studies, the same type of droughts should be considered for all streams. Here the winter droughts in cold and temperate regions are excluded.

Before starting to make any drought calculations, one has to find out whether discharges might be reduced during the winter because of low temperatures and if so, the summer discharges have to be identified. An easy and common way to do this is by defining summer and winter seasons as fixed seasons. This should be done for each catchment separately. A possible procedure is described in Hisdal et al. (2001), who specified the end of the summer season as the last day of the last month with a mean monthly temperature above the freezing point. Months with a mean monthly temperature below the freezing point constitute the winter season and the summer could be considered to start in the first month with a mean monthly temperature above 0 ºC. However, the winter precipitation first has to melt before it contributes to the discharge and this snow melt period can go on for several weeks with temperatures above 0 ºC. In streams whose catchments receive a lot of snow during the winter a clear discharge maximum, the spring flood, occurs during the period of snowmelt. These high discharge values which are caused by winter precipitation should not be included in the summer season and therefore Hisdal et al. (2001) determined the average timing of the spring flood and specified the summer season to start at the end of the spring flood (Figure 3.20).

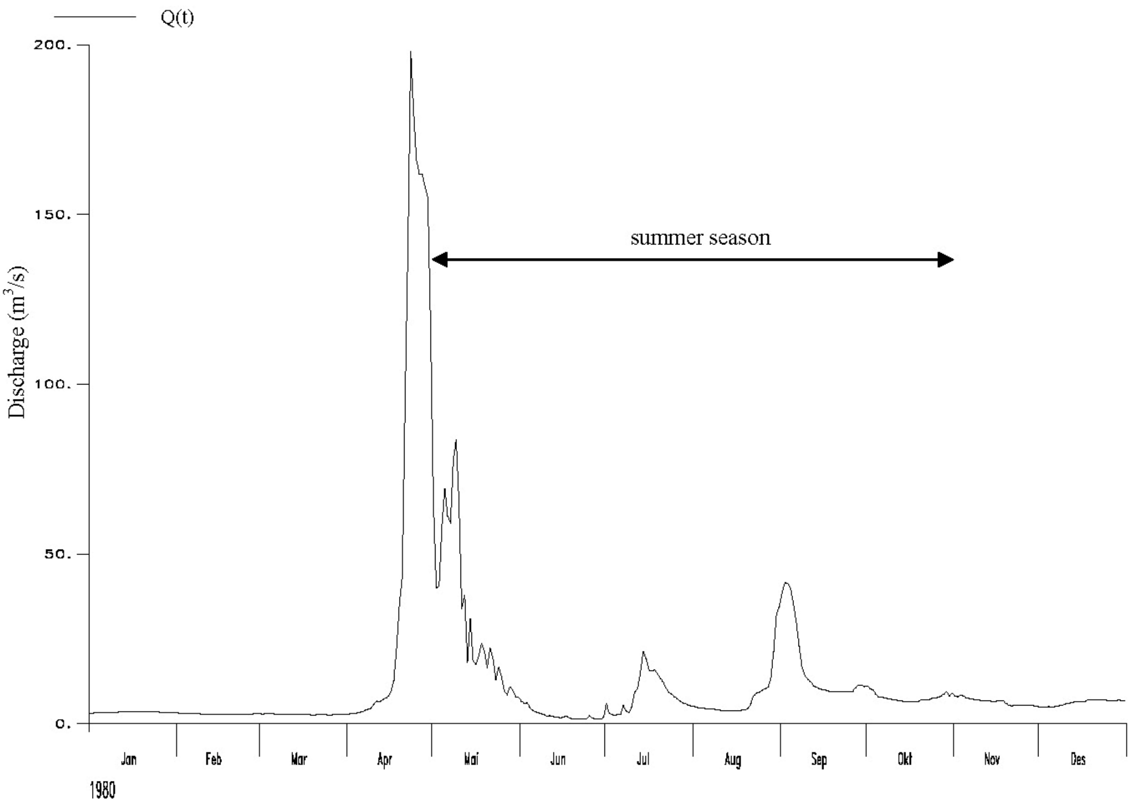


Figure 3.20 Hydrograph of Inva at Kudymkar, Russia with the chosen summer period (1 May – 31 October).

The advantage of this method is that the only additional information needed is the mean monthly temperatures, which in case of no catchment temperature data can be estimated from the climate normals of a region. But this method also includes several problems. First of all the real starting and ending dates of the summer and winter seasons vary from year to year and by choosing fixed dates for them mistakes are not only done in the division of the discharges into summer and winter discharges but also drought events might be split or incorrectly classified into summer and winter droughts. This problem could be reduced if a series of daily temperature values corresponding to the discharge series is available and the dates of the summer season could be defined for each year separately. Whenever specifying summer and winter seasons, temperature is probably the most common and easiest additional data available on a daily basis, but of course other data such as type of precipitation or snow cover can also be used.

One has to be aware that the dates of the seasons not only vary from year to year, but possibly also between different parts of one catchment. Especially in catchments that cover a large altitude range or have a large areal extension the period during which precipitation falls as snow and possibly establishes a stable snow cover in some parts, while it continues to fall as rain in other parts, can be relatively long. In some catchments it lasts even throughout the whole winter. This is the case for the rivers Rhine at Lobith, the Netherlands as well as Hurunui at Mandamus, New Zealand. The Rhine is a relatively extreme example, since its catchment even covers several climate zones and an area of 160 800 km^2. The lower parts of the catchment experience on average only continuous frost periods of several days, while the frost periods in the mountainous areas last for several months. For Rhine as well as for Hurunui the percentage of low flow values is also less during the winter season than during the summer season and the percentiles $Q90$ and $Q70$ are slightly higher for all-year data than for only summer data. This is the opposite as for streams with a frost season in the whole catchment, Inva in Russia as well as Lågen and Ostri in Norway. How the seasons should be specified when long periods of different seasons within the catchment occur depends again on the purpose of the study. If the focus is on the site, generally, one might want to specify the seasons as they occur at the station, but if a series of drought events is required to be iid also drought events which are only partially caused by frost, have to be excluded and the summer seasons should be shortened.

For the River Rhine it was decided to conduct the calculations of drought characteristics twice, one time for the whole year and the second time seasonally excluding a frost season from December until February. For the other streams experiencing frost in a cold or temperate climate the following winter seasons were specified: Hurunui at Mandamus, New Zealand: 1.7. – 31.10., Lågen at Rosten, Norway: 1.10. – 14.6., Inva at Kudymkar, Russia: 1.11. – 30.4. and Ostri at Liavatn, Norway: 1.10. – 14.6.

Since it is common to apply low flow indices as threshold level, the questions arises whether the threshold level as well should be based only on the data of the summer season or on data of the whole year. The most frequently applied low flow indices as threshold levels are percentiles from the FDC. As it can be seen on the example of Lågen at Rosten, Norway in Figure 3.21, the FDCs of only summer data can differ considerably from those of the complete data record. This counts in particular for the high percentiles in the low flow range. For example the $Q90_S$ of the chosen summer period (15.6. – 30.9.) is with 17.08 m^3/s more than five times as high as the $Q90_Y = 2.97$ m^3/s. The lowest observed discharge during the summer season is $Q_{min,S}$ = 6.30 m^3/s, and with a threshold level equal to $Q90_Y$ no summer droughts would occur. Hence, when a percentile from the FDC is to be used as threshold level, the FDC should be based only on summer data. For the calculation of the FDC_S an accurate specification of the end of the summer as well as of its start are necessary and the differences in the FDCs of summer periods differing by two weeks can also be seen in Figure 3.21. It is important that the summer season starts after the spring flood instead of before, since a larger number of high discharge values shifts the discharge values in the low flow range to higher percentiles and the values of the percentiles increase.

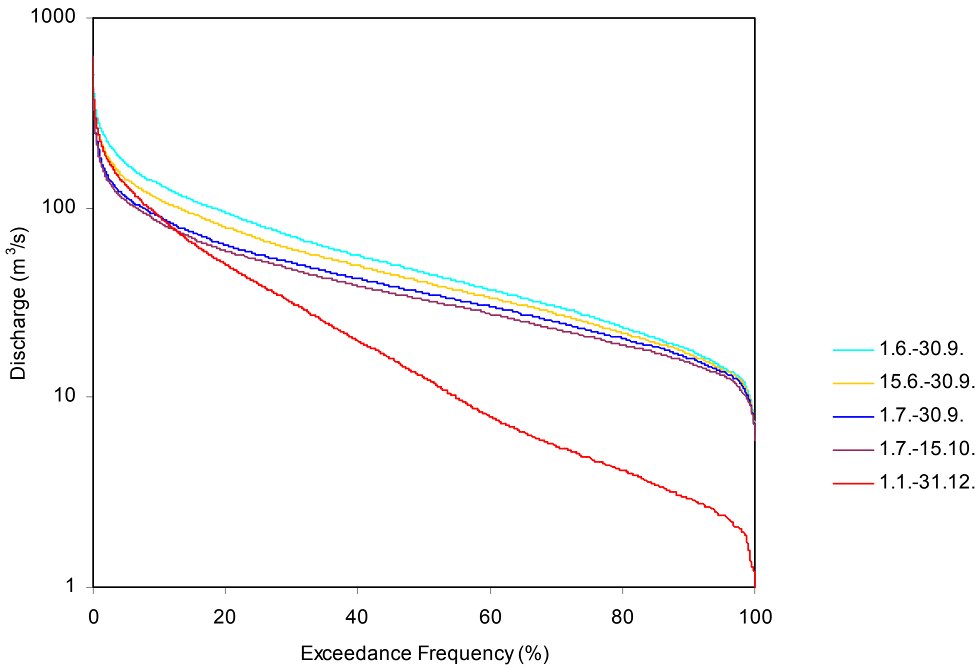


Figure 3.21 FDCs for Lågen at Rosten, Norway for a summer season with starting and ending dates varying by two weeks as well as for the whole year.

In this study the two pooling-procedures, IT-method, conducted by NIZOWKA2003, and SPA, represent two different ways to select only summer drought events from a discharge series. In both cases a fixed summer period has to be chosen prior to the selection of the events. In the SPA then only the discharge data from the chosen summer season are considered, whereas in NIZOWKA2003 all data are considered and drought events were defined as summer droughts when their major part (at least half of its duration) belonged to the summer season. This was done prior to the pooling of mutually dependent drought events. The disadvantage of the fixed seasons used in the SPA is that drought events might easily be split or incorrectly classified as summer or winter droughts. For example in years with a late-ending summer, only the first part of a summer drought which continues after the predefined end of the summer is detected and considered to be a summer drought, but it is registered to be shorter and less severe than it actually was. In years with an early winter on the other hand parts of the winter drought are considered to be a (short) summer drought in the end of the summer. It is less likely to incorrectly detect drought events at the beginning of the summer season, since discharges at that time are still relatively high due to the snow melt. With the way of identifying drought events used in NIZOWKA2003 it is tried to avoid the inclusion of parts of winter droughts of an early winter in the summer drought PDS and at the same time it is more likely that long summer droughts in a long summer are recorded correctly without cutting them of. With the use of fixed seasons in the SPA method, one is more likely to combine periods with $Q(t) < Q_0$ to mixed summer-and-winter droughts when pooling. This is less likely done with the IT-method, since the periods with $Q(t) < Q_0$ are classified as either summer or winter droughts prior to pooling.

Another problem is that it can happen that a summer drought, especially a severe one, has not been ended before temperatures fall below the freezing point. It will not be ended until temperatures rise again. This drought is not a pure summer drought anymore. It is not an easy question of how to handle and interpret these unfinished summer or combined summer and winter droughts. Applying the above described method of fixed summer and winter periods together with the SPA, these droughts are considered to be finished on the first day of the winter season. Another possibility would be to let the duration of the drought event increase, but not the deficit volume. In the IT-method it depends whether the longer part of the drought belongs to the summer or the winter season. In case of a long winter season it can happen that severest summer droughts are not considered since they turn into a long winter drought.

2. Frost season in a winter dry climate

A special case in the global data set is the catchment of Pecos River in New Mexico, USA. The catchment lies in a region, where the winter season is characterised by low precipitation amounts as well as temperatures below the freezing point. In addition, it spans over a large altitude range and the average duration of the frost period varies from 6 months at Truchas, the highest point in the catchment, to 2 – 3 months at the measuring station (WRCC, 2003). For Pecos River the specification of the summer and the winter season is difficult, since the start of the summer is not marked through a clear snowmelt peak in the hydrograph. This is because the amount of snow accumulated during the winter is small and probably the melt water can take the usual way through the soil and groundwater instead of causing large amounts of fast overland runoff. In addition, the beginning of the rainy season occurs only a little later than the snowmelt period but also varies from year to year. On average it causes much higher discharge values than the snowmelt, but still the effects of these two events can not always be distinguished in the hydrograph. Also drought events can occur during the period of the average occurrence of the snowmelt and the start of the rainy season, and then it is unclear, whether they are caused by still low temperatures or by low precipitation amounts. So the same problems as at the end of the summer season exist now also at the beginning of the summer season. Because of the missing discharge peak at the end of the winter it can also happen that drought events start during the summer season, continue throughout the whole winter and then also continue into the next summer. For Pecos River the seasons were specified as summer: 1.3. – 30.11. and winter: 1.12. – 1.4.

3. Wet and dry seasons

Other climate regions not experiencing a frost season also have several types of droughts due to seasonal differences such as a wet and a dry season. These droughts are all summer droughts caused by a lack of precipitation and a loss of water through high evapotranspiration, but they originate from different weather systems and as such they do not have the same characteristics and do not belong to the same statistical population of droughts. For example in a Mediterranean climate droughts during the dry season are usually sever and very long compared to the much shorter drought events occurring during the wet season. Still both types of droughts are important for the water budget and water management of the region. And it is often required to obtain streamflow drought characteristics for the different drought types separately. For the derivation of some drought characteristics this is even necessary. A frequency analysis requires a series of drought events to be identically and independently distributed, but a series of drought events caused by different weather systems is not identically distributed.

Commonly the wet and dry season droughts are easily split up after obtaining the drought series from the whole data series. And a previous definition of start and end of the wet and dry season is not necessary. Neither is it advisable as it will likely split severe drought events. In many cases wet season droughts get automatically excluded from a series of drought events by choosing a low enough threshold level, since drought events during a wet period usually occur on a higher discharge level than dry season droughts. Otherwise, or when the wet-season droughts are to be studied, the separation of the obtained drought events can be done by looking at a single drought characteristic or at a combination of several, such as duration and time of occurrence. For example the histogram of a drought duration series derived for the river Sabar, Spain clearly shows two different drought populations (Figure 3.22).

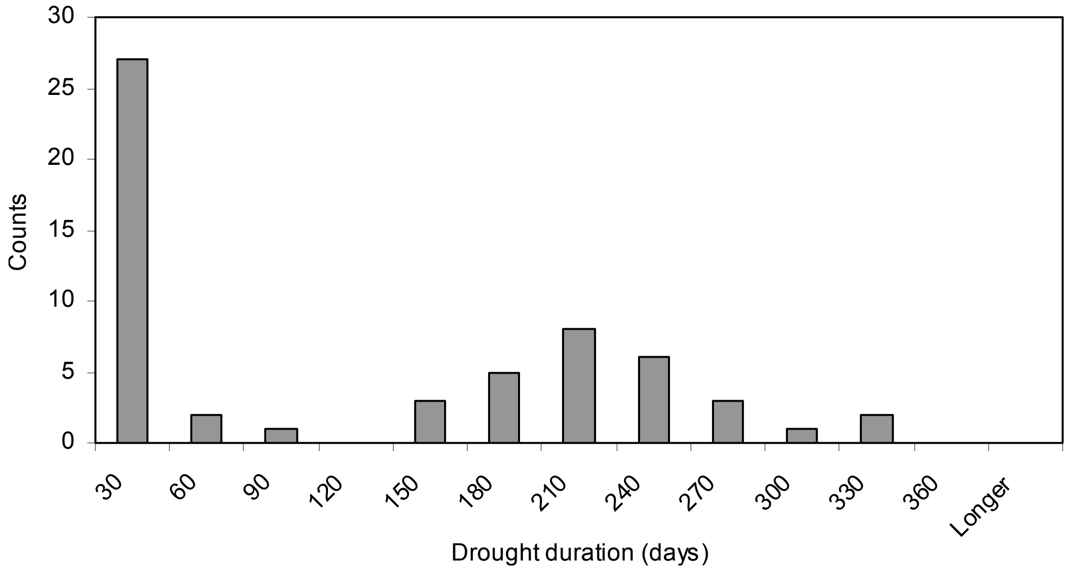


Figure 3.22 Histogram of the drought duration of Sabar at Alfartanejo, Spain (derived with the SPA and a threshold level of *Q*40) showing several populations of drought events.

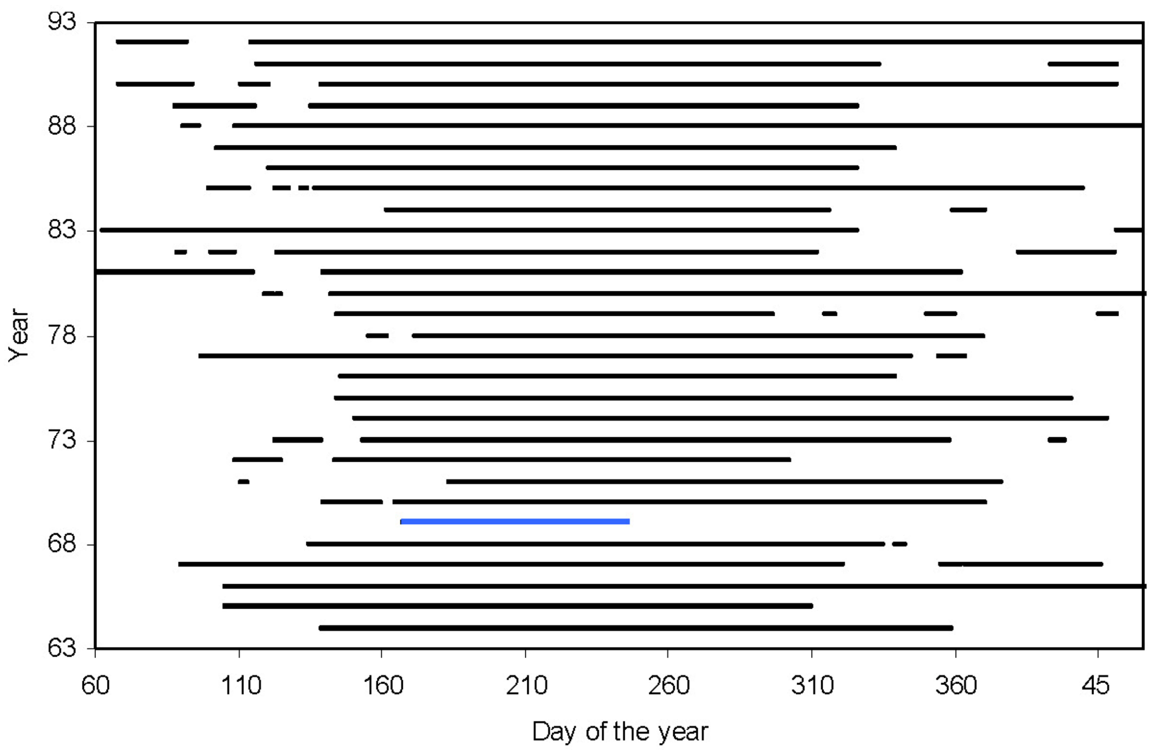


Figure 3.23 Occurrence plot of the drought events of Sabar at Alfartanejo, Spain, derived with the SPA and a threshold level of *Q*40. (Note that the scale on the axis of abscissae starts on day 60, since for Sabar the year was chosen to start on March 1st).

To identify events in the possibly overlapping tails of the two distributions additional information can be obtained from the occurrence plot of the droughts (Figure 3.23). For example the 77-day long drought occurring in 1969 actually is a short dry-season drought. By only looking at the duration of the droughts, the drought of 1969 would have been classified as a wet-season drought.

Another way of obtaining a series of only dry-season droughts from the complete records is to derive an annual maximum series (AMS) instead of a partial duration series (PDS). But this leaves one with less information on dry-season droughts, if in some years more than one dry-season drought occur. If also multi-year droughts occur, the size of the block of the maximum series has to be enlarged from one year to maybe three or five years. This means however that information is lost from the years without multi-year droughts, because then only the largest event within three or five years gets selected.

When conducting a frequency analysis with NIZOWKA2003 the used PDS has also to be derived with the IT-method within NIZOWKA2003. This leaves one with the following options to derive a PDS of identically distributed events:

(a) deriving a PDS of only wet-season droughts or dry-season droughts, based on predefined seasons as it was described for frost influenced streams,
(b) the parameter d_{min} to remove minor droughts can be set so high, that all wet-season droughts are excluded and only the long dry-season droughts are considered,
(c) use of a lower threshold level, so that only droughts of the dry season are considered.

The disadvantage of options (b) and (c) is, that only dry-season droughts can be studied. But here it was decided to test these to options on streams experiencing a wet and a dry season, since the first option will already be tested for frost influenced streams.

Other specified periods

Predefining fixed dates for seasons can also be reasonable to do, when one is interested in a specific time of the year, not as a climate characteristic but for example as an interest of nature, such as the spawning season of a certain fish species, the season of incubation of water birds, or when deciding on a period when it is allowed to fish. Studying only a specific time of the year one has to be aware of the statistical problems connected to it, since one will obtain a mixture of complete drought events as well as tails and beginnings of events.

3.2.2.3 Year shift

Working with discharge data from all over the world the choice of the hydrological year can have some major influence on the selection of the events and has to be chosen very carefully. This is important for annual calculations or the derivation of drought characteristics which are based on annual calculations. It turned out that neither the calendar year nor the hydrological year as it is defined nationally is appropriate for all streams to derive drought characteristics. Also not one unique year can be applied to all streams; it rather has to be defined for each stream separately but according to the same regime characteristic. In the following the starting and ending date of the chosen year will be referred to as 'year shift'.

Using the dates of the calendar year is inappropriate since then the year shift falls into different parts of the hydrological regime for different streams and for some streams on the southern hemisphere into the middle of the summer low flow season. This makes calculations for different streams incomparable. Also the dates of the hydrological year are not always applicable, especially not for a comparable study, since the reasoning for the definition of the hydrological year varies between different countries, sometimes corresponding to special hydrological features of the region. For example in snow influenced areas, the start of the winter season also determines the start of the hydrological year (e.g. Switzerland, October 1st or Norway, September 1st) whereas in other regions the hydrological year starts after the winter precipitation has drained (e.g. Denmark, June 1st). In New Zealand on the other hand the hydrological year does not differ from the calendar year, since New Zealand contains too many different climate zones to allow one hydrological year to be suited for all the existing hydrological regimes.

For drought studies the most serious problems related to the date of the year shift occur if a low flow period is split between two years. Therefore an advisable date for the year shift is the middle of the high flow period or within an unconsidered season, e.g. a winter season with frost. The middle of the high flow period is chosen rather than its beginning or end, since then also unusually early or long lasting low flow periods are the least likely to be split.

Dividing one low flow period onto two different years, would cause in this study the following problems:

1. For the calculation of the *MAM*(*n*-day) the *n*-day minima is chosen for each year. If one low flow period belongs to two succeeding years because of the date of the chosen year shift, and the lowest discharge values occur around the year shift, the chosen annual

minima of two succeeding years occurred actually only a few days or weeks after each other. So a severe low flow period will contribute twice to the series of annual minima while a less severe low flow period will not be considered at all. When not the 1-day annual minimum is chosen but a 10- or 30-day annual minimum, it might even happen that the data from the same days is considered in both years. Also for the calculation of the return periods for *AM*(*n-day*)-values, it is a prerequisite that the events are mutually independent. Similar problems arise for any kind of annual calculations, such as the derivation of an AMS of drought events, which is not done in this study.

2. As explained in Section 3.2.1 one option of excluding longer periods of incorrect data is to omit one year of data. If the omitted year would start and end in the low flow season, the risk is high to cut off drought events in both years and information about the droughts is lost. Depending on the method to derive a drought characteristic, cut-off events might also complicate the procedure significantly or even lead to incorrect results. For example the distribution of a drought characteristic and all statistics derived from it become incorrect when some events are cut-off and considered to be shorter and less severe than they actually were. When the omitted year starts and ends in the high flow season only information from one low flow season is lost and drought events are less likely to be cut off.

3.2.2.4 Zero-flow periods

Zero-flow periods influence the calculation of the deficit volume and one has to be aware of the different information content of the deficit volumes of intermittent streams compared to perennial streams. During zero-flow periods the actual temporal behaviour of the stream's discharge is forced to stop, while the discharge would probably continue to decrease, if it had not already reached zero. But since nothing like a negative discharge exists this behaviour can not be measured and the deficit volumes during zero-flow periods do not increase with increasing drought duration in the same way as during flow periods. This has two consequences:

a) that the deficit volumes of intermittent streams can not be interpreted in the same way as those of perennial streams.
b) for a frequency analysis of deficit volumes of intermittent streams the data should be treated as censored data during the periods when the river falls dry.

However, NIZOWKA2003 does not include a special treatment for censored data and therefore no estimates of deficit volumes for intermittent streams are made in this study. For calculations of the drought duration zero-discharges do not have to be treated in a special way, so the frequency analysis can still be conducted for drought durations.

3.2.2.5 Incompletely observed drought events

When deriving a PDS of drought events, it can happen that the series includes incompletely observed events at the start or end of the series, even though the year shift and thereby the start and end of the used time series have been selecting carefully and according to the considerations discussed in the previous section. For a further analysis no incomplete events should be included in the PDS and the discharge series should be shortened accordingly by whole years, since excluding those events implies the consideration of a drought period as a drought-free period and including them changes the characteristics of the PDS.

The used implementation for the SPA-pooling-procedure as well as NIZOWKA2003 exclude drought events from the final PDS which are not finished on the last day of the discharge series, without reducing the record length accordingly. NIZOWKA2003 also omits drought events which could have started prior to the first day of the discharge series, whereas in the SPA method these events are assumed to start on the first day and are thus included in the PDS. The PDS derived with both methods have therefore to be checked for incomplete events and drought-free periods caused by the exclusion of incomplete events and new PDS have to be derived for a shortened periods of record.

3.3 Used data series

Following the data considerations as outlined in the previous sections, the data series as presented in Table 3.2 resulted. For the River Rhine a series of all-year data as well as one of only summer data are included since the influence of frost varies strongly within the catchment.

Table 3.2 Used periods of the global data set and, if necessary, the chosen summer season

Stream, Site	Available period	Available number of years	Summer	Used period	Omitted years[2]	Used number of years
Honokohau Stream, Honokohau	1.5.1922 - 30.9.1996	74	-	1.4.1935 - 31.3.1988		53
Dawib, Dawib	7.12.1978 - 30.9.1993	14	-	1.2.1986 - 31.1.1991		5
Pecos River, Pecos	1.1.1930 - 30.9.1999	69	1.3.-30.11.	1.12.1930 - 30.11.1998		68
Elandrivierie, Elands River Drift	13.12.1963 - 30.11.1992	29	-	1.12.1979 - 30.11.1992	87/88	13
Bagamati River, Sundurijal	1.1.1970 - 31.12.1995	26	-	1.9.1970 - 31.8.1995	73/74, 86/87, 91/92	22
Sabar, Alfartanejo	1.10.1963 - 30.9.1993	30	-	1.3.1964 - 28.2.1993		29
Arroyo Seco, Soledad	1.10.1901 - 30.9.1999	98	-	1.3.1931 - 28.2.1999		68
Ray, Grendon Underwood	1.10.1962 - 31.12.1999	37	-	1.3.1963 - 28.2.1997	82/83, 85/86-92/93	26
Lambourn, Shaw	1.10.1962 - 31.1.2000	37	-	1.4.1963 - 31.3.1999		36
Lindenborg, Lindenborg Bro	1.06.1925 - 31.12.1997	72	-	1.3.1960 - 28.2.1997		37
Ngaruroro, Kuripapango	20.9.1963 - 31.12.2000	37	-	1.9.1964 - 31.8.2000	65/66, 78/79, 86/87, 87/88	34
Hurunui, Mandamus	27.10.1956 - 30.6.2000	43	1.11.-30.6.	1.7.1960 - 30.6.2000		40
Lågen, Rosten	27.3.1917 - 2.5.2003	86	15.6.-30.9.	1.10.1918 - 30.9.2002		84
Inva, Kudymkar	1.1.1936 - 31.12.1995	60	1.5.-31.10.	1.11.1936 - 31.10.1995	86, 88, 90, 93	56
Rhine, Lobith	1.1.1901 - 30.12.1993	93	-[1] 1.3.-30.11.	1.12.1901 - 30.11.1993		92
Ostri, Liavatn	1.1.1965 - 14.11.2000	35	15.6.-30.9.	1.10.1965 - 30.9.1999		34

[1]two series are chosen, one of all-year data and one of only summer data

[2]combined year numbers represent one hydrological year as used here.

4 Evaluation

4.1 Low flow characteristics

4.1.1 Flow duration curve and percentiles

FDCs can be calculated for data records for every length, representing always the chosen period. In Figure 4.1 it can be seen on the example of the Rhine at Lobith, the Netherlands, how the FDCs based on one year and 10 years of data differ from the ones based on 50 years and 93 years. The two FDCs based on 50 and 93 years are very much alike. This suggests that for long record lengths the FDC is less sensitive to the chosen period and that it is a good indicator for the overall discharge variability. Standardised FDCs for the global data set are displayed in Figure 4.1. Even though FDCs do not reveal whether the variability is a short-term variability as in the case of Honokohau Stream at Honokohau, Hawaii or a seasonal variability as in the case of Bagamati River at Sundurijal, Nepal Figure 4.2, they are a good graphical method to compare the overall variability of different streams. For the perennial streams FDCs standardised by *Q*50 are displayed in Figure 4.2, where a logarithmic scale is used for the axis of ordinates. For the intermittent and ephemeral streams FDCs are standardised by *MQ* and displayed in Figure 4.3. Percentiles from the FDC which are commonly used as low flow indices are presented in Table 4.1. The applicability of the FDC in general and its percentiles as low flow indices is evaluated in Table 4.2

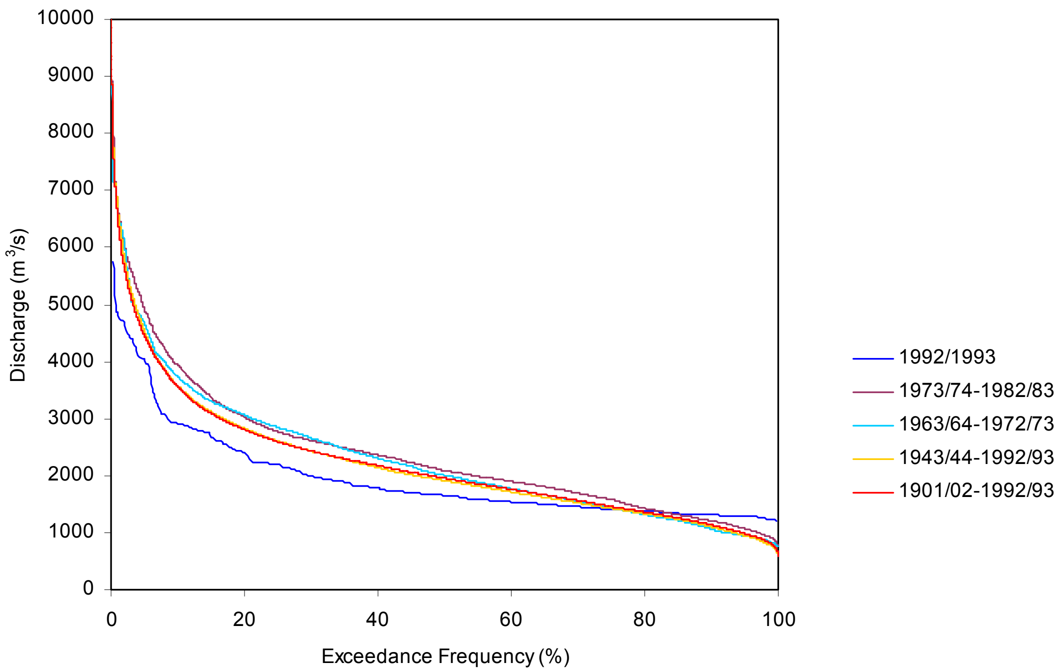
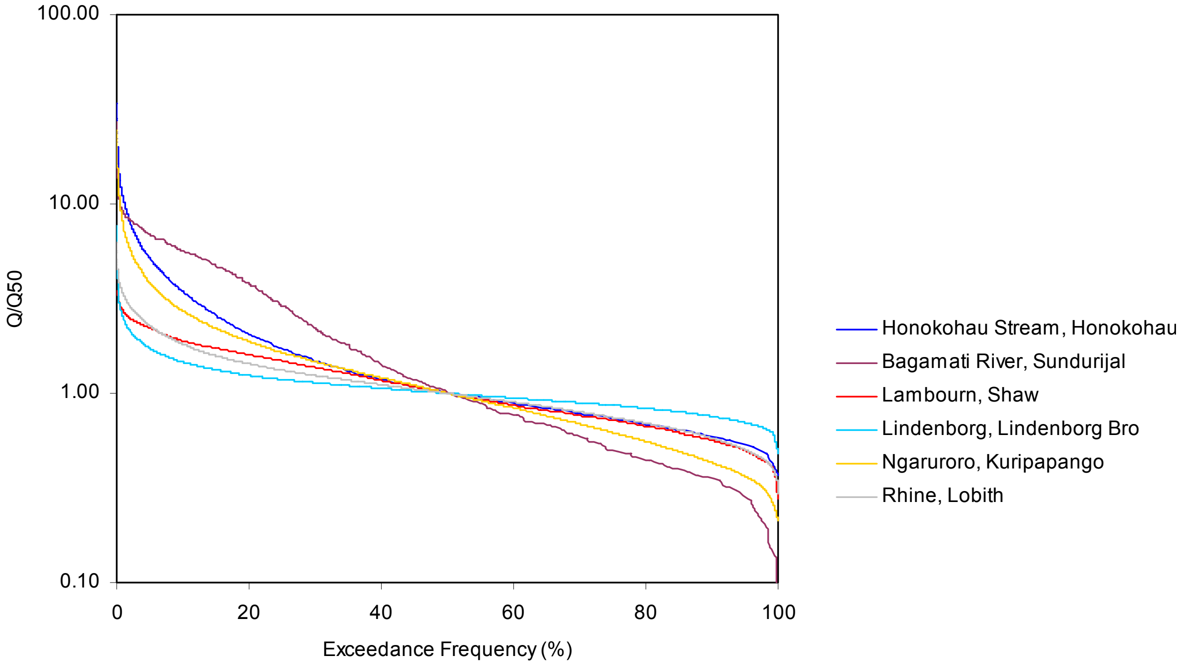


Figure 4.1 FDCs for Rhine at Lobith, the Netherlands for data series of varying length (1, 10, 50 and 93 years) and for two series of 10 years from different periods.



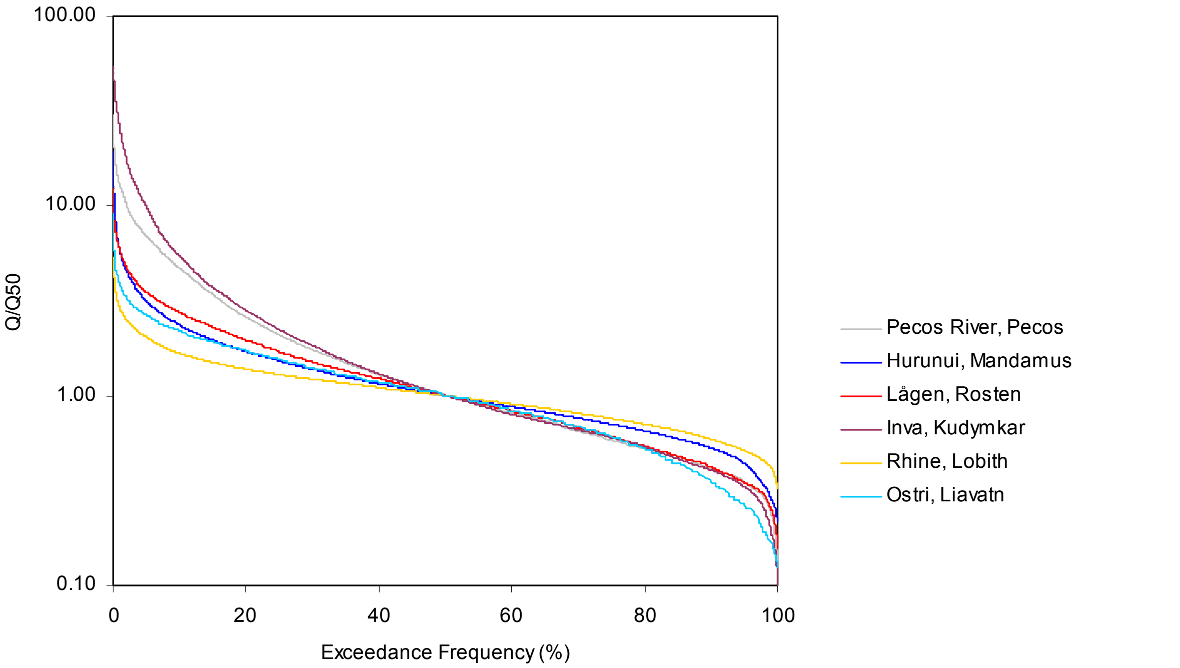


Figure 4.2 Standardised FDCs of the perennial streams of the global data set. Upper: Perennial streams without frost influence. Lower: Perennial streams with frost influence.

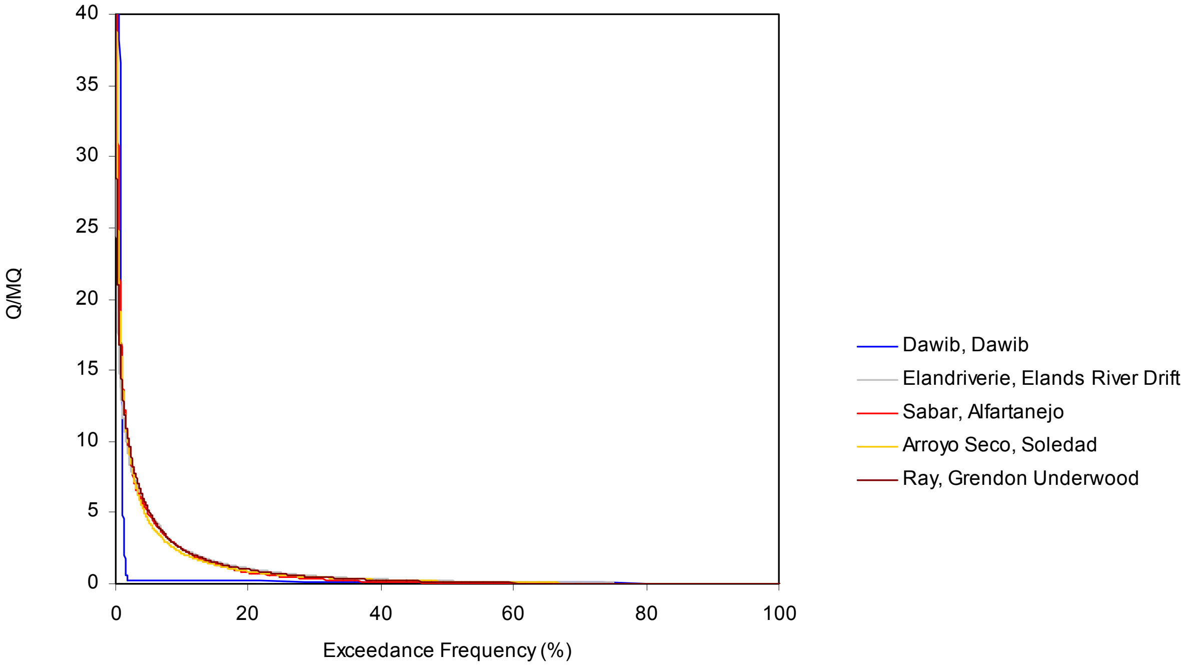


Figure 4.3 Standardised FDCs for the intermittent and ephemeral streams of the global data set.

Table 4.1 Percentiles from the FDC commonly used as low flow indices for the global data set, given as specific discharges. For frost influenced streams, the percentiles are calculated only from summer data

Stream, Site	***Q95/Area*** (l/(s·km^2))	***Q90/Area*** (l/(s·km^2))	***Q70/Area*** (l/(s·km^2))	***Q50/Area*** (l/(s·km^2))
Honokohau Stream, Honokohau	30.87	33.45	43.74	59.18
Dawib, Dawib	0.00	0.00	0.00	0.00
Pecos River, Pecos	1.33	1.56	2.43	3.84
Elandriverie, Elands River Drift	0.03	0.09	0.25	0.66
Bagamati River, Sundurijal	8.24	10.59	17.65	30.59
Sabar, Alfartanejo	0.00	0.00	0.00	0.00
Arroyo Seco, Soledad	0.00	0.00	0.36	1.21
Ray, Grendon Underwood	0.00	0.00	0.05	0.58
Lambourn, Shaw	3.17	3.59	4.83	6.37
Lindenborg, Lindenborg Bro	7.05	7.63	9.00	10.10
Ngaruroro, Kuripapango	12.00	14.17	22.75	32.99
Hurunui, Mandamus	15.08	18.21	26.20	34.39
Lågen, Rosten	8.03	9.73	15.59	23.01
Inva, Kudymkar	0.93	1.13	1.84	2.79
Rhine, Lobith (year)	6.11	7.06	9.70	12.18
Rhine, Lobith (summer)	6.10	7.00	9.61	11.88
Ostri, Liavatn	22.51	29.15	57.23	83.96

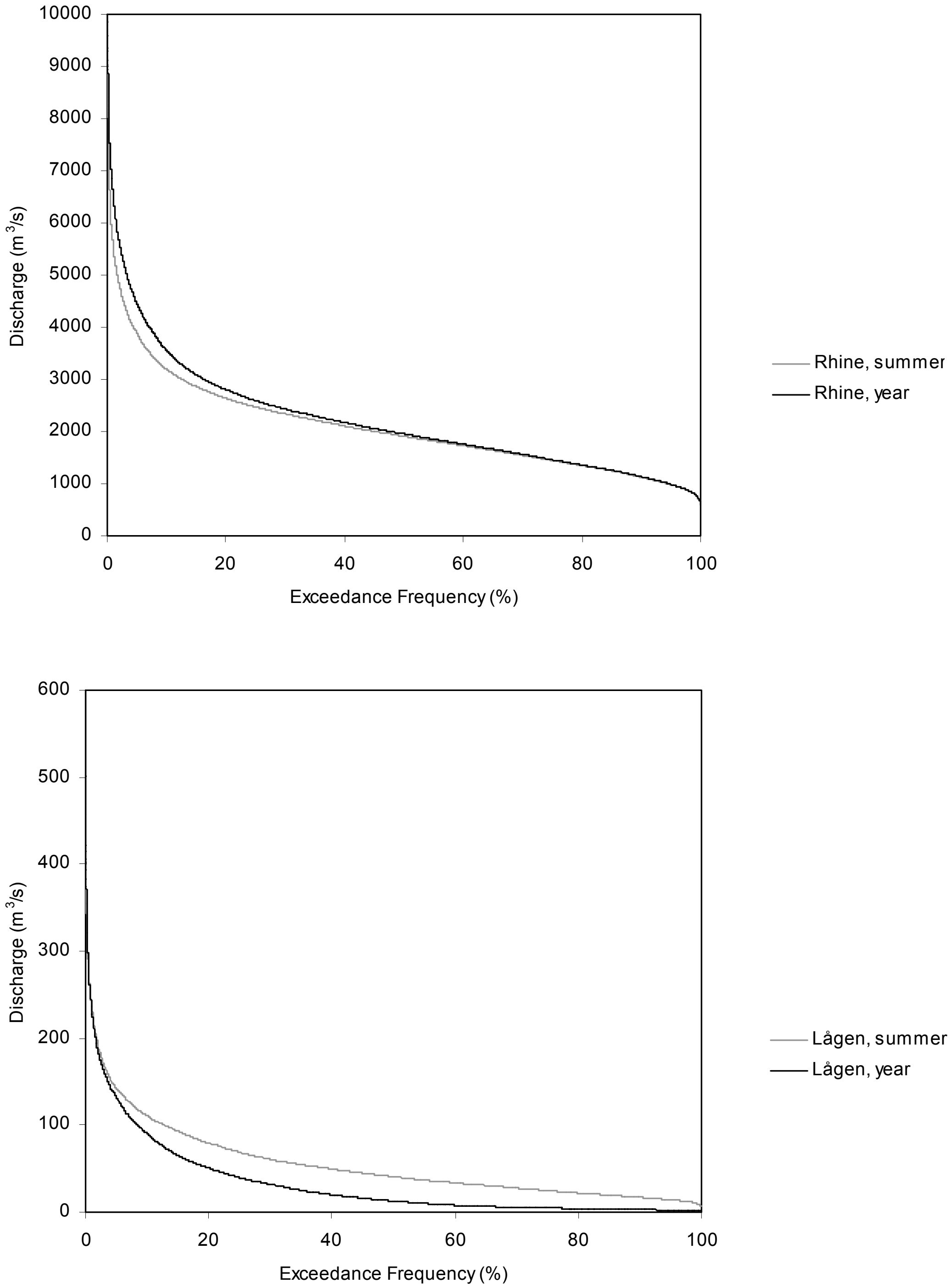


Figure 4.4 FDCs for the summer season and for the whole year, showing different influences of the frost season. Upper: Rhine at Lobith, the Netherlands. Lower: Lågen at Rosten, Norway.

Table 4.2 Evaluation of the applicability of the FDC and its percentiles for streams with different streamflow types

Streamflow type	Evaluation
Perennial	The FDC is a good graphical method to display a stream's discharge variability. The percentiles of different streams are comparable and high percentiles can be used as low flow indices and as threshold levels deriving comparable drought series for the different streams.
Perennial, seasonal	The FDC and its percentiles are very sensitive to the chosen summer season (Section 3.2.2.2) and for studying summer droughts a precise specification of the summer season is necessary. The FDC is also a good measure to judge the influence of the frost season on a stream's discharge variability, for example the small influence on low discharges during the frost season at the Rhine as compared to Lågen (Figure 4.4).
Intermittent	The FDC can be calculated for the *whole year* as well as for *wet season* and *dry season* separately. Based on the *whole year*, it displays the variability as well as the percentage of zero-flow values, which is an important quantity characterising intermittent streams. Offers to choose low flow indices greater than zero in coherence with the percentage of zero-flow values, by using lower percentiles.
Ephemeral	The percentage of zero-flow values is an important quantity which is also displayed by the FDC.

4.1.1.1 Global comparison

The standardised FDCs and its percentiles can be used to compare the variability of streams from different regions and with different regimes. When also intermittent and ephemeral streams are considered the FDCs have to be standardised by the mean daily discharge, *MQ* rather the *Q*50. The FDC does not show whether the variability is caused by short-term fluctuations or by a high seasonal variability. When FDCs of frost influenced streams are included, one has to decide whether the winter season should be included or whether only the summer season of all streams is to be considered. This should especially be considered when one wants to compare drought series of different streams with a common percentile as threshold level, since for example the all-year FDC from a stream in a temperate climate also differs from its summer FDC. If for frost influenced streams the percentile is calculated from the summer FDC this should maybe also be done for the other streams who experience a summer and winter season. For intermittent and ephemeral streams the percentage of zero-flow values can be used in addition to the percentiles in order to describe the FDC.

4.1.2 Mean annual *n*-day minimum

MAM(1), *MAM*(10) and *MAM*(30), which are common low flow indices, are presented for the global data set in Table 4.3. For intermittent streams the percentage of non-zero values in the AM(*n*-day)-series provides additional information and is as well given in Table 4.3. For perennial streams it is always 100 %. In general, it is important that an appropriate year shift is chosen for the calculations of an AM(*n*-day)-series and the MAM(*n*-day) (Section 3.2.2.3). For streams with a frost season the specification of the summer season is less complicated as for the calculation of the FDC, since the possible high discharges during the spring flood at the start of the summer do not influence the MAM(*n*-day). For larger averaging intervals also a few days of winter low flows at the end of the summer have no influence.

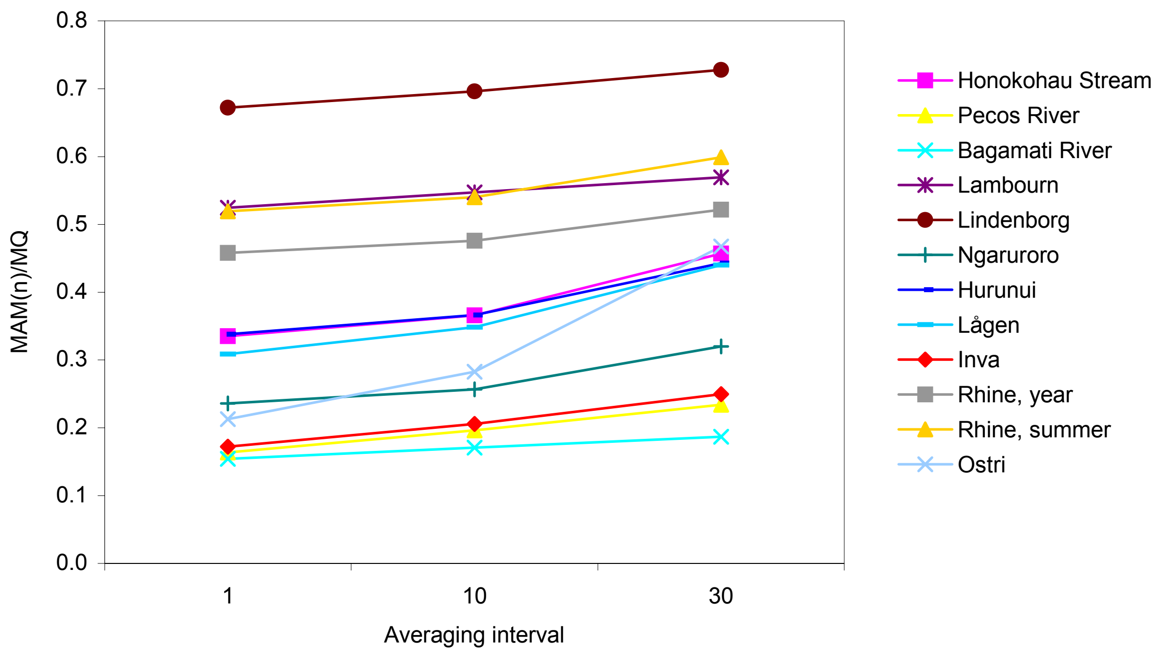


Figure 4.5 *MAM*(1), *MAM*(10) and *MAM*(30) standardised with *MQ* for all perennial streams of the global data set.

In Figure 4.5 standardised *MAM*(1), *MAM*(10) and *MAM*(30) are displayed for all perennial streams, with and without frost season. This allows to compare the flow behaviour of the different streams during low flow periods. A steep gradient between *MAM*(30) and *MAM*(1) indicates short droughts, either caused by the flashiness of a stream (e.g. Honokohau Stream) or by only short low flow periods (e.g. Ostri). A flat gradient on the other hand indicates a rather constant discharge for longer times during low flow periods (e.g. Bagamati River and

Lambourn). The applicability of the MAM(n-day) for streams with different streamflow types is evaluated in Table 4.4. The information content of AM(n-day)-values can also be increased with a frequency analysis.

Table 4.3 Mean annual n-day minima of non-frost influenced data, for the global data, given as specific discharge values, and the percentage of non-zero values in the annual n-day minimum series, $c_{non\text{-}zero}\,AM(n\text{-day})$ of the intermittent and ephemeral streams

Stream, Site	***MAM*(1)/*Area*** (l/(s·km²))	$c_{non\text{-}zero}$ ***AM*(1)** (%)	***MAM*(10)/*Area*** (l/(s·km²))	$c_{non\text{-}zero}$ ***AM*(10)** (%)	***MAM*(30)/*Area*** (l/(s·km²))	$c_{non\text{-}zero}$ ***AM*(30)** (%)
Honokohau Stream, Honokohau	32.96		36.04		44.97	
Dawib, Dawib	0.00	0.0	0.00	0.0	0.00	0.0
Pecos River, Pecos	1.20		1.44		1.72	
Elandriverie, Elands River Drift	0.05	75.0	0.08	75.0	0.12	91.7
Bagamati River, Sundurijal	9.73		10.77		11.76	
Sabar, Alfartanejo	0.00	0.0	0.00	0.0	0.00	0.0
Arroyo Seco, Soledad	0.14	51.5	0.15	51.5	0.18	52.9
Ray, Grendon Underwood	0.00	7.8	0.00	11.5	0.00	38.5
Lambourn, Shaw	3.80		3.96		4.12	
Lindenborg, Lindenborg Bro	7.32		7.58		7.93	
Ngaruroro, Kuripapango	11.09		12.05		14.23	
Hurunui, Mandamus	15.25		16.54		19.98	
Lågen, Rosten	9.65		10.89		13.76	
Inva, Kudymkar	1.19		1.42		1.72	
Rhine, Lobith (year)	6.29		6.54		7.17	
Rhine, Lobith (summer)	6.75		7.02		7.78	
Ostri, Liavatn	20.96		27.81		45.97	

Table 4.4 Evaluation of the applicability of MAM(n-day) for streams with different streamflow types

Streamflow type	**Evaluation**
Perennial	MAM(n-day) are suitable low flow indices, which in contrast to the percentiles from the FDC include also a duration aspect and additional information can be obtained through the comparison of MAM(n-day)s with different averaging intervals.
Perennial, seasonal	For the study of summer droughts the period with low flows caused by frost has to be excluded, then it can be used as for perennial streams without frost influence. Compared to percentiles from the FDC, MAM(n-day)-values are less sensitive to an accurate specification of the summer as season.

(→ Table continued on next page)

Table 4.4 (continued)

Intermittent	The use of MAM(*n*-day)-values, based on *whole year* data, is limited, since they are usually zero. Only for larger averaging intervals, i.e. higher *n*-values, the MAM(*n*-day) of some streams can be non-zero. Can also be calculated for only the *wet season*; calculated from only *dry season* data, the results are the same as from all-year data. The maximal and mean annual zero-flow duration might be more informative indices.
Ephemeral	MAM(*n*-day)-values are always zero and provide therefore no new information. The maximal and mean annual zero-flow duration are more informative indices.

4.1.2.1 Global comparison

MAM(*n*-day)s are informative low flow indices for perennial streams and streams with and without frost season can easily be compared. Since the information content is limited for ephemeral and intermittent streams, MAM(*n*-day)s are usually not suitable low flow indices to analyse streams with different streamflow types.

4.1.3 Comparison of the low flow indices

In Table 4.5 the low flow indices *Q*95, *Q*90, *Q*70, *MAM*(1), *MAM*(10) and *MAM*(30) as well as *Q*50 and *MQ* are ranked in increasing order for each stream of the global data set. The ranking for the ephemeral and intermittent streams differs from the perennial streams, since several or all of the low flow indices are equal to zero. Otherwise, the *MQ* always represents the highest value, rank 8, and *Q*50 the second highest value. For all twelve perennial streams *Q*70 is on rank 6 and *MAM*(30) on rank 5, except for Honokohau Stream, where *MAM*(30) is higher due to its flashiness throughout the whole year. *MAM*(10) is equally often on rank 4 and 3, as well is *Q*90 on rank 4. Otherwise *Q*90 is four times on rank 3 and twice on rank 2. *MAM*(1) is twice on rank 3, seven times on rank 2 and three times it represents the lowest value. In most cases represents *Q*95 the lowest discharge value, i.e. for nine of the 12 perennial streams. The exceptions are Pecos River at Pecos, USA, Ngaruroro at Kuripapango, New Zealand and Ostri at Liavatn, Norway. For the two streams with frost influence, Pecos River and Ostri, this could mean that few days of winter low flows are included in the chosen summer season in several years and for Ngaruroro that low flow periods do not last very long.

Table 4.5 Ranking of the low flow indices, $Q50$ and MQ for each stream of the global data set in increasing order. In case of frost influence all measures are derived from only summer data

Stream, Site	Q95	Q90	Q70	MAM (1)	MAM (10)	MAM (30)	Q50	MQ
Honokohau Stream, Honokohau	1	3	5	2	4	6	7	8
Dawib, Dawib	1	1	1	1	1	1	1	8
Pecos River, Pecos	2	4	6	1	3	5	7	8
Elandriverie, Elands River Drift	1	4	6	2	3	5	7	8
Bagamati River, Sundurijal	1	3	6	2	4	5	7	8
Sabar, Alfartanejo	1	1	1	1	1	1	1	8
Arroyo Seco, Soledad	1	1	6	3	4	5	7	8
Ray, Grendon Underwood	1	1	5	1	1	5	7	8
Lambourn, Shaw	1	2	6	3	4	5	7	8
Lindenborg, Lindenborg Bro	1	4	6	2	3	5	7	8
Ngaruroro, Kuripapango	2	4	6	1	3	5	7	8
Hurunui, Mandamus	1	4	6	2	3	5	7	8
Lågen, Rosten	1	3	6	2	4	5	7	8
Inva, Kudymkar	1	2	6	3	4	5	7	8
Rhine, Lobith (year)	1	4	6	2	3	5	7	8
Rhine, Lobith (summer)	1	3	6	2	4	5	7	8
Ostri, Liavatn	2	4	6	1	3	5	7	8

4.2 Deficit characteristics

4.2.1 IC-method

4.2.1.1 Parameter selection

In contrast to the SPA method, the IC-method includes parameters that have to be chosen. Tallaksen et al. (1997) optimised the parameter choice for two perennial streams in a temperate climate. But their IC-method consisted of an IT-criterion as well as an IV-criterion. Zelenhasić & Salvai (1987) used only an IT-criterion, but they did not do any optimisation procedure for it. Since in this study as well only an IT-criterion is used and in addition the method is to be applied to streams of different regime types a sensitivity analysis for the choice of the interevent time, t_c of the IT-criterion was conducted.

The sensitivity analysis is based on the mean values of the deficit volume as well as the real drought duration (Equation 2.9). The real drought duration is used rather than the full drought duration, since the full drought duration also considers the interevent periods within pooled drought events and therefore increases stronger with increasing t_c. Here the sensitivity analysis can not be used to find the optimal value of t_c, since the mean values of both deficit characteristics are strictly increasing with increasing t_c. However, it can be used to compare the results to those from Tallaksen et al. (1997) to decide whether the value of $t_c = 5$ days can also be used when no additional IV-criterion is applied and for streams with varying flow behaviour. Tallaksen et al. (1997) could optimise t_c, since they defined the total pooled deficit volume according to Equation 2.6, subtracting the interevent excess volume, thus the total pooled deficit volume is not strictly increasing with t_c but approaches an upper limit. When this upper limit is reached the drought events are pooled in the most critical way, recording the largest deficit volumes, and t_c is chosen to be optimal.

For the sensitivity analysis perennial streams as well as intermittent streams belonging to different climate regions and showing different hydrological regimes were chosen. Streams experiencing a frost season were not considered, since the available method to select only summer droughts was not considered to be stable enough in order to base a sensitivity analysis on a drought series derived with this method. But the summer regime of a frost influenced stream can in most cases be compared to those of perennial streams in a temperate climate and the optimal parameter value can be adopted from these. This might not be true for streams which are strongly affected by glaciers, since during hot periods the amount of melt water from the glaciers increases. The perennial streams used for the sensitivity analysis were the rivers Lindenborg (at Lindenborg Bro, Denmark) and Ngaruroro (at Kuripapango, New Zealand) from a temperate climate. Lindenborg is situated in a flat area and the catchment of Ngaruroro belongs to a mountainous region. Further, the Bagamati River (at Sundurijal, Nepal), experiencing a monsoon climate, and the Honokohau Stream (at Honokohau, Hawaii), experiencing a tropical climate were chosen. The intermittent streams were Sabar (at Alfartanejo, Spain) with a dry climate and 50.9 % of zero-flow values, Arroyo Seco (at Soledad, USA) with a temperate summer-dry climate and 12.9 % of zero-flow values and Ray (at Grendon Underwood, United Kingdom) with a temperate climate without any dry season and 26.4 % of zero-flow values.

The sensitivity analysis for the IT-criterion, t_c is conducted without removing any minor drought events. For the perennial streams a threshold level of $Q_0 = Q90$ is chosen. For intermittent streams the threshold levels are chosen depending on their percentage of zero-flow values. As a result the MQ for Sabar, $Q70$ for Arroyo Seco and $Q50$ for Ray were applied. The mean values of a drought event series increase with increasing t_c. In order for the

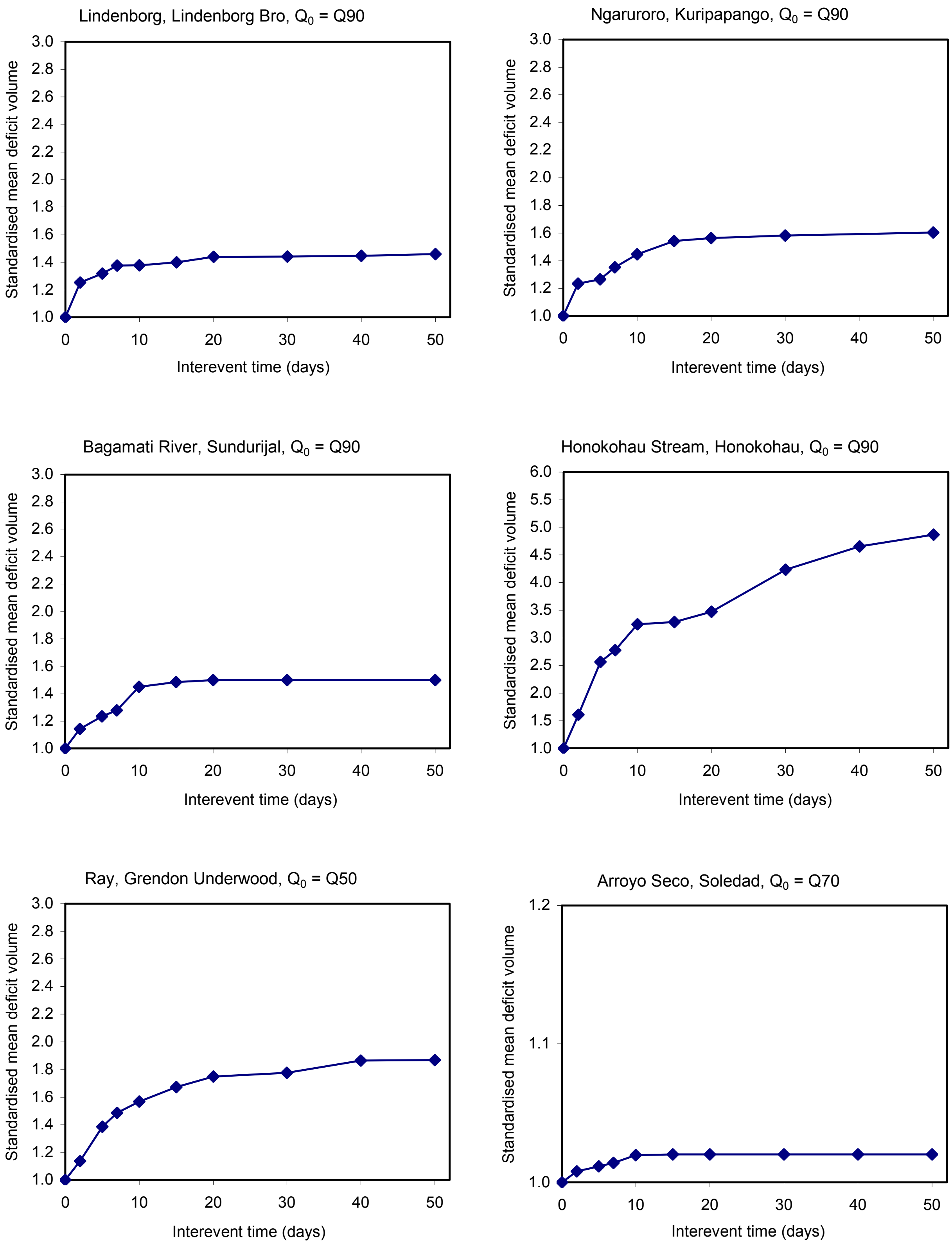


Figure 4.6 Relationship of the standardised mean deficit volume and the interevent time for four perennial (upper and middle) and two intermittent (lower) streams.

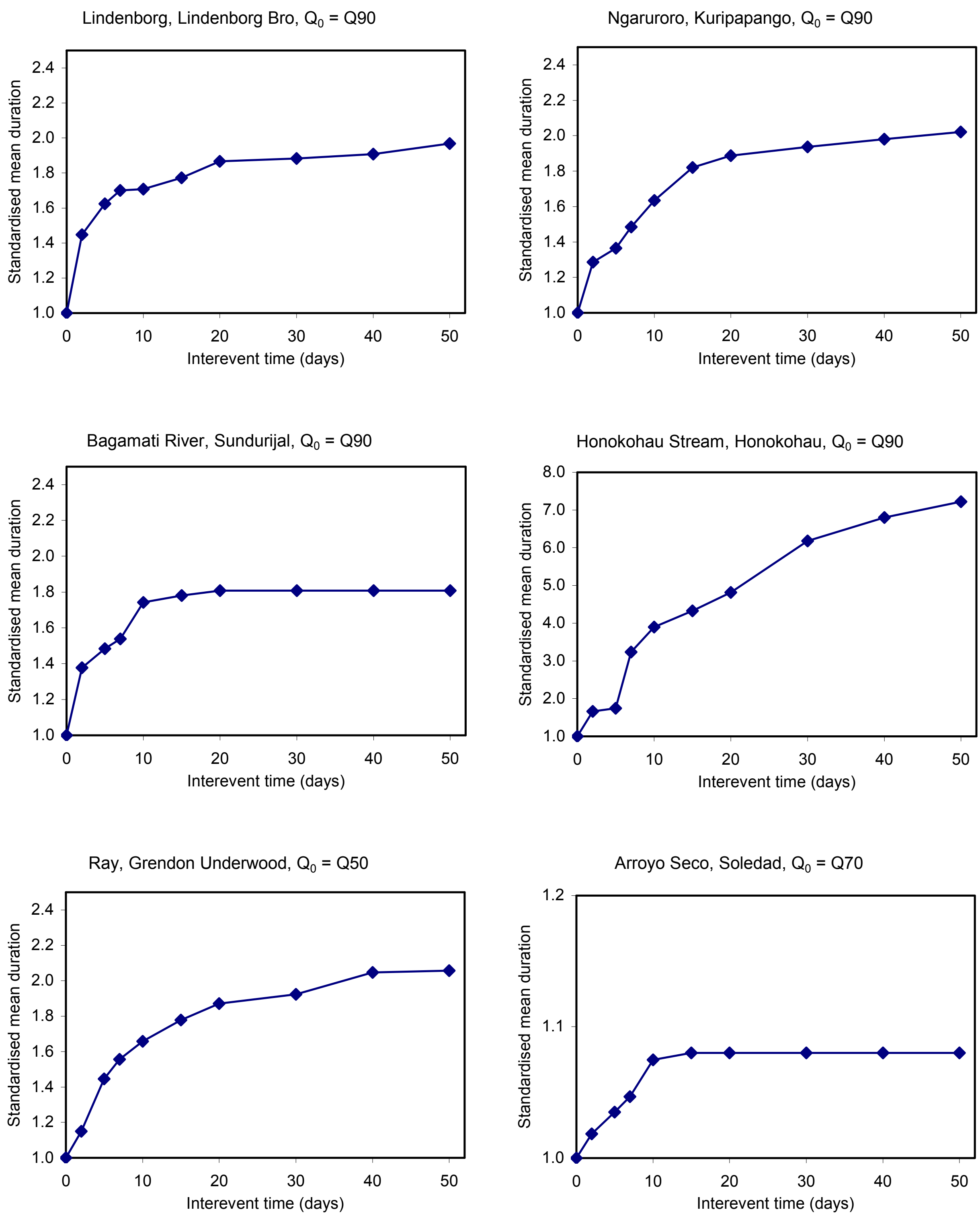
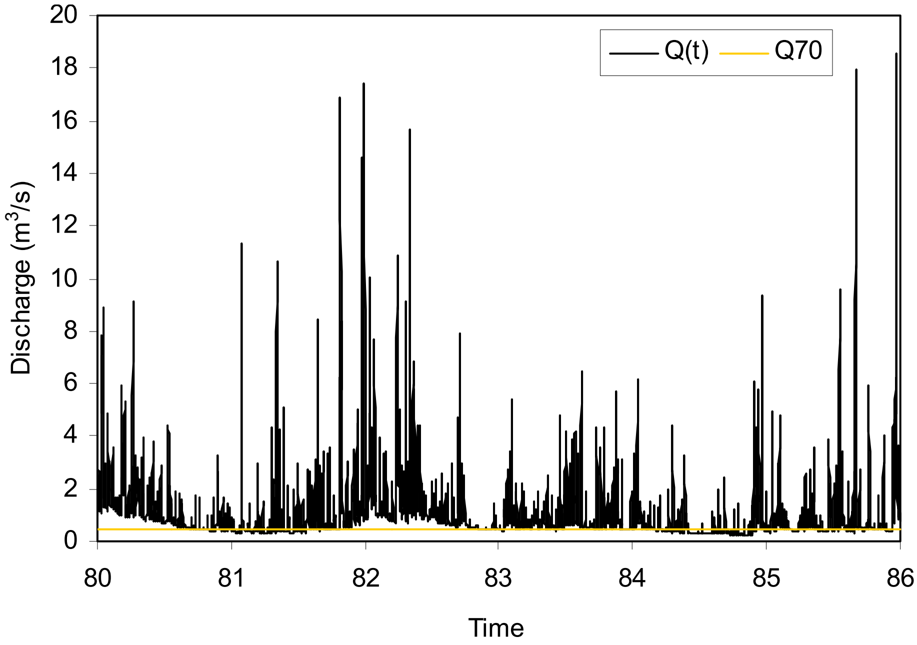


Figure 4.7 Relationship of the standardised mean real duration and the interevent time for four perennial (upper and middle) and two intermittent (lower) streams.

sensitivity analysis not to be influenced neither by a possibly large number of minor droughts nor by the number of drought events which are pooled, the deficit characteristics of the AMS of non-zero values are analysed rather than of a PDS. The mean values for the deficit characteristics are calculated for t_c = 0, 2, 5, 7, 10, 15, 20, 30, 40 and 50 days, in which the interevent time of 0 days represents the original series, since no events are pooled. The mean deficit volumes/duration are standardised by the mean deficit volume/duration of the series with $t_c = 0$ day. The relationships between the standardised mean deficit volume and the interevent time, t_c are displayed in Figure 4.6 and the relationships between standardised mean real drought durations and t_c in Figure 4.7.

The relationships between t_c and the mean deficit volume and mean real drought duration of Sabar, Alfartanejo were determined by an increasing number of multi-year droughts and were therefore not used further. For regimes with a clear dry season and little day-to-day variability the mean deficit volume and duration of the AMS are increasing with t_c until basically all droughts of one season are pooled. Nearly all droughts of one season are pooled at a t_c of 20 days for Lindenborg, 15 days for Ngaruroro, and 10 days for Bagamati River and Arroyo Seco. Whereas for the streams Ray and Honokohau Stream, whose hydrographs show a much higher day-to-day variability and whose regimes show more than only one dry and wet season (Figure 3.2), the mean deficit volume and drought duration continue to increase until a t_c of 40 days and 50 days respectively. The day-to-day variability is especially high for Honokohau Stream also during low flow periods (Figure 4.8). The pooled mean deficit characteristics of its drought events increase much faster and to a much higher multiple of the mean deficit characteristics of the non-pooled AMS, compared to the streams with one low flow season. For the perennial streams all curves show a smaller gradient at around a t_c of 3 to 5 days, which corresponds to the results of Tallaksen et al (1997). This suggests that for most perennial streams the recommendation from Tallaksen et al. (1997) can be accepted and the IT-method can than still be conducted with the definition of the total deficit volume as it is used here. For flashy perennial streams as Honokohau Stream with a frequent interruption of low flow periods, however, the interevent excess volume has to be considered in some way, either through subtracting the interevent excess volume from the total deficit volume or through an additional IV-criterion. It can be expected that with the more precisely defined total deficit volume, when the interevent excess volumes are subtracted, and the use of an $t_c = 5$ days, several pooled deficit volumes will even be negative, since the interevent excess volume can be larger than the deficit volumes and probably another t_c-value should be



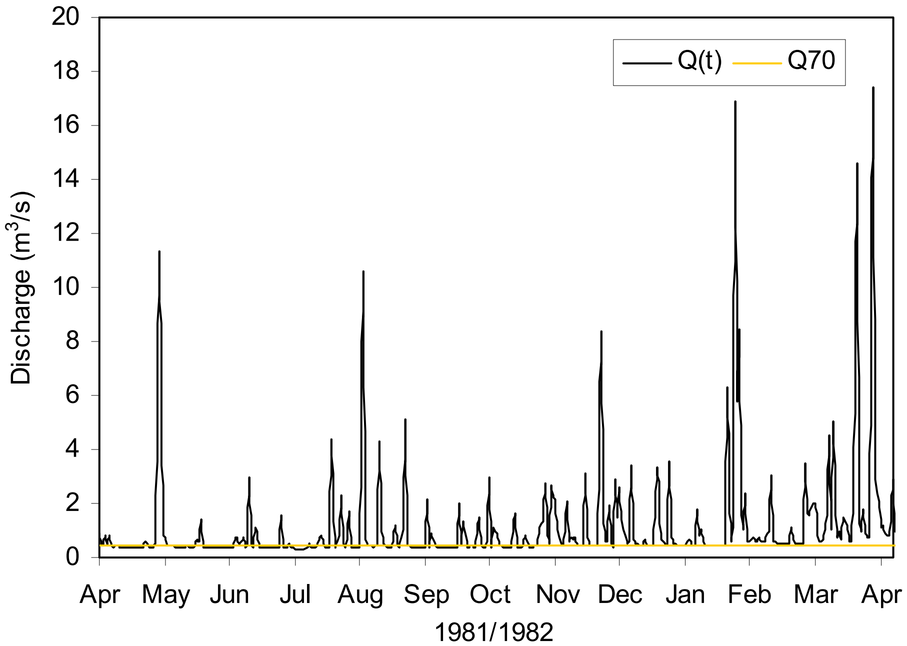


Figure 4.8 Hydrographs of Honokohau Stream at Honokohau, Hawaii. Upper: 1980 to 1985 to illustrate the annual variability (note that the station year for Honokohau Stream starts on April 1st). Lower: One year with a low mean daily discharge illustrating the frequent interruption of periods with $Q(t) < Q70$.

recommended for flashy streams. For flashy intermittent streams such as the river Ray on the other hand the consideration of the interevent excess volume might not be a good solution either, since during zero-flow periods the growth of the deficit volume is disturbed and interevent excess volume and deficit volume can not be compared in the same way as for perennial streams. For intermittent streams which experience a clear dry season and do not show such a continuous flashiness throughout the year the choice of interevent time seems to have only little influence as long as the threshold level is low enough so that the number of multi-year droughts stays small. This is because the zero-flow periods during the dry season are usually not interrupted by longer flow periods. If one wants to study only the drought events occurring within the wet season, possibly the same value for t_c can be recommended as for perennial streams, but a separated t_c sensitivity analysis for the wet season could not be conducted here.

4.2.1.2 Application of the IC-method

Drought series with $t_c = 5$ days have been derived for the global data set with threshold levels of *Q*90 and *Q*70 for the perennial streams and higher discharge values for the intermittent streams. The results for $Q_0 = Q70$ are summarised in Table A3.1 (Appendix 3) and for $Q_0 = Q90$ the results are presented together with the comparison of the IC-method and the SPA in Table 4.9 - Table 4.11. The applicability on streams of the different streamflow types is evaluated in Table 4.6.

When the percentiles of the FDC are used as threshold levels, they allow to make comparisons of the deficit characteristics of different perennial streams, but one has to be aware that they also depend on the used record length. So if one looks at two different periods from one stream of a relatively short duration, say 10 years and derives for both periods the series of drought events with a threshold level of the 90-percentile of the corresponding period, one will observe more or less the same drought behaviour for both periods, even if one period mostly consists of wet years and the other one mostly of dry years. This is because of course also the value of *Q*90 of the wet-year period is higher than the one of the dry-year period. So one has to keep in mind that the information content and the comparability of drought series depends very much on the record lengths of the discharge series, also when the same percentile is applied as threshold level.

4.2.1.3 Global comparison

For perennial streams the results from the parameter optimisation show the advantage and the greater accuracy of defining the total deficit volume of a pooled event as the sum of the single deficit volumes minus the interevent excess volume, rather than ignoring the interevent excess volume, since droughts can not considered to be mutually dependent anymore when the interevent excess volume is bigger than the single deficit volumes and should therefore not be pooled.

Table 4.6 Evaluation of the applicability of the IC-method for streams with different streamflow types

Streamflow type	Evaluation
Perennial	With $t_c = 5$ days the IT-method is a good method to derive a series of mutually independent drought events for most perennial streams. All deficit characteristics such as deficit volume, duration and time of occurrence can be derived. The method is not advisable for flashy streams.
Perennial, seasonal	Drought events can be derived from all-year data and then be classified as summer or winter droughts prior to pooling, no events are cut-off or additionally combined to mixed summer-and-winter droughts by pooling. The way of identifying the summer droughts is an important factor and two possibilities are evaluated in Section 4.6.2.
Intermittent	Drought series of the whole year can be derived and wet- and dry-season droughts can also be studied separately. *Wet season*: the IT-method can be used as for perennial streams. When zero-flow periods occur also during the wet season the IT-method is probably more advisable than the IC-method including also an IV-criterion, but the two methods could not be compared here. *Dry season*: Pooling is less important and often not necessary, since larger droughts are not so frequently split into mutually dependent droughts.
Ephemeral	Pooling is not necessary, the length of time without the occurrence of any flow event determines whether a streamflow drought occurs or not. Drought events can thus be derived with the IT-method with $t_c = 0$ day, $Q_0 = 0$ (when droughts are defined as periods with $Q \leq Q_0$) and additionally, a minimal drought duration above which zero-flow periods are considered as droughts or a minimum interevent excess volume which is considered to terminate a drought. The duration of zero-flow periods as well as the excess-volume of flow events or the annual discharge are better indicators for droughts.

The IT-method can be used to derive comparable drought duration series of perennial and intermittent streams with a $t_c = 5$ days for non-flashy streams. For a comparison of intermittent and perennial streams the IT-method without an additional IV-criterion is even favourable, since the deficit volumes of the two streamflow types are not comparable. For fast-responding flashy streams t_c has to be optimised when the interevent excess volume is considered to make the results comparable to those of non-flashy streams. The deficit volumes of perennial streams and intermittent streams or intermittent streams with different percentages of zero-discharge days can not be compared.

4.2.2 MA(n-day)-filter

4.2.2.1 Parameter selection

The results from the IT-method showed that for perennial streams, it is in general favourable to consider the interevent excess volume when pooling dependent droughts; for streams with a flashy hydrograph such as Honokohau Stream it is even necessary. The MA(*n*-day)-filter was therefore tested as pooling method for Honokohau Stream as well as for Lindenborg. When smoothing a daily discharge curve with a MA(*n*-day)-filter the ratio of the discharge values above the threshold level to those below the threshold level determines the total deficit volume of the pooled events. This is similar to subtracting the interevent excess volume from the total pooled deficit volume as in the IC-method.

Since the MA(*n*-day)-filter might introduce an additional dependency between successive drought events if the events are less than *n* days apart, it was conducted in two steps. First an MA(*n*-day)-filter was applied and in the second step the obtained events were pooled by the IT-method with $t_c = n$ days. To determine the optimal *n*, again the mean deficit volume and mean real drought duration of the AMS of non-zero values were calculated and standardised by the mean deficit volume/real drought duration of the non-pooled AMS. When using a MA(*n*-day)-filter the mean deficit volume is not strictly increasing with an increasing *n*. The relationship between the mean deficit volume and *n* can thus be used to determine the optimal value for *n*. Since a MA(*n*-day)-filter modifies the time series, *n* should be chosen as small as possible, i.e. when the mean deficit volume reaches a maximum or when it levels out. AMS were obtained with MA(*n*-day)-filters of $n = 5$, 10, 15, 20, 25 and 30 days, and again a threshold level of $Q_0 = Q90$ was applied. The relationship between the standardised mean deficit volume and *n* for Lindenborg and Honokohau Stream is displayed in Figure 4.9 and between the standardised mean real drought duration and *n* in Figure 4.10. For Lindenborg the mean deficit volume as well as the mean real drought duration are nearly constant for moving average intervals from 10 to 20 days, as it was observed by Tallaksen et al. (1997) and the use of a MA(10-day)-filter can be recommended. For Honokohau Stream the mean deficit characteristics reach a maximum for a moving average interval of 15 days, which is therefore considered the optimal moving average interval for Honokohau Stream to assess the severe drought events.

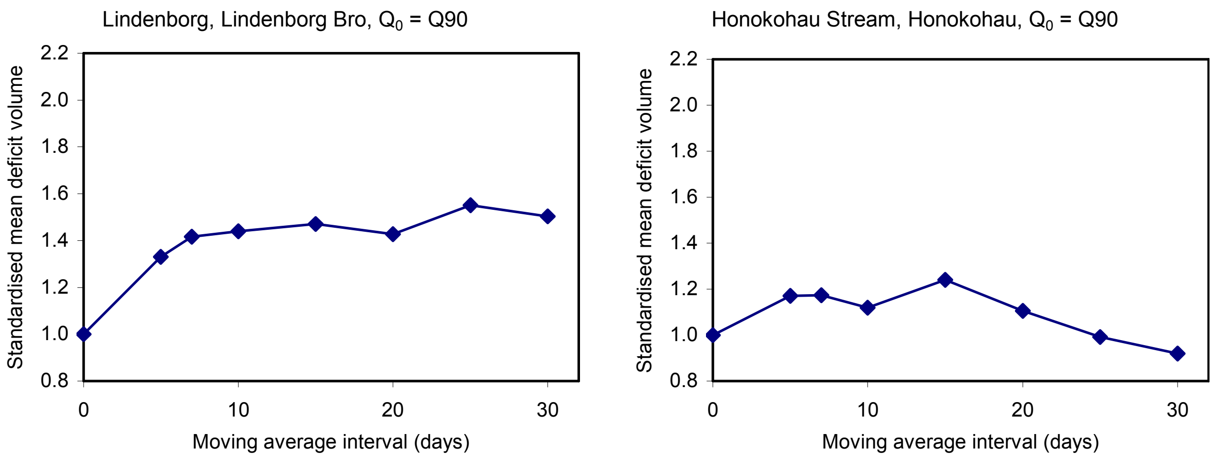


Figure 4.9 Relationship between the standardised mean deficit volume and the moving average interval for Lindenborg at Lindenborg Bro, Denmark and Honokohau Stream at Honokohau, Hawaii.

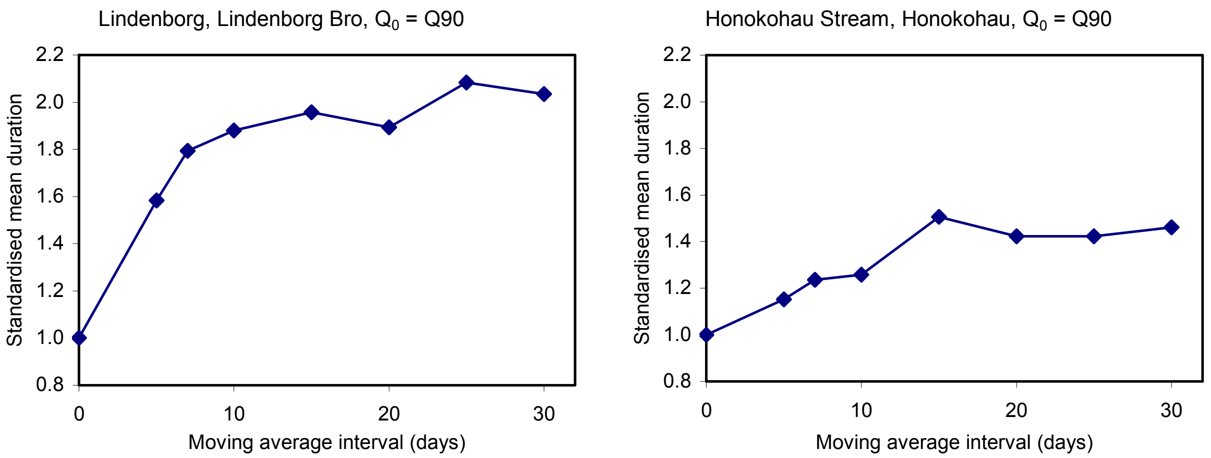


Figure 4.10 Relationship between the standardised mean duration and the moving average interval for Lindenborg at Lindenborg Bro, Denmark and Honokohau Stream at Honokohau, Hawaii.

4.2.2.2 Application of the MA(n-day)-filter

The MA(*n*-day)-filter was applied as pooling-procedure, deriving PDS of drought events, for Honokohau Stream at Honokohau, Hawaii and Lindenborg at Lindenborg Bro, Denmark. For Honokohau Stream an averaging interval of $n = 15$ days was used and for Lindenborg an averaging interval of $n = 10$ days. Compared to the results obtained by the IT-method (Figure 4.6 and Figure 4.7), the mean deficit characteristics from the MA(*n*-day)-method are much less for Honokohau Stream, whereas they are slightly larger for Lindenborg, due to the removal of minor droughts (Figure 4.9 and Figure 4.10). This again demonstrates the importance of considering the interevent volume in a pooling-procedure for rivers with flashy hydrographs.

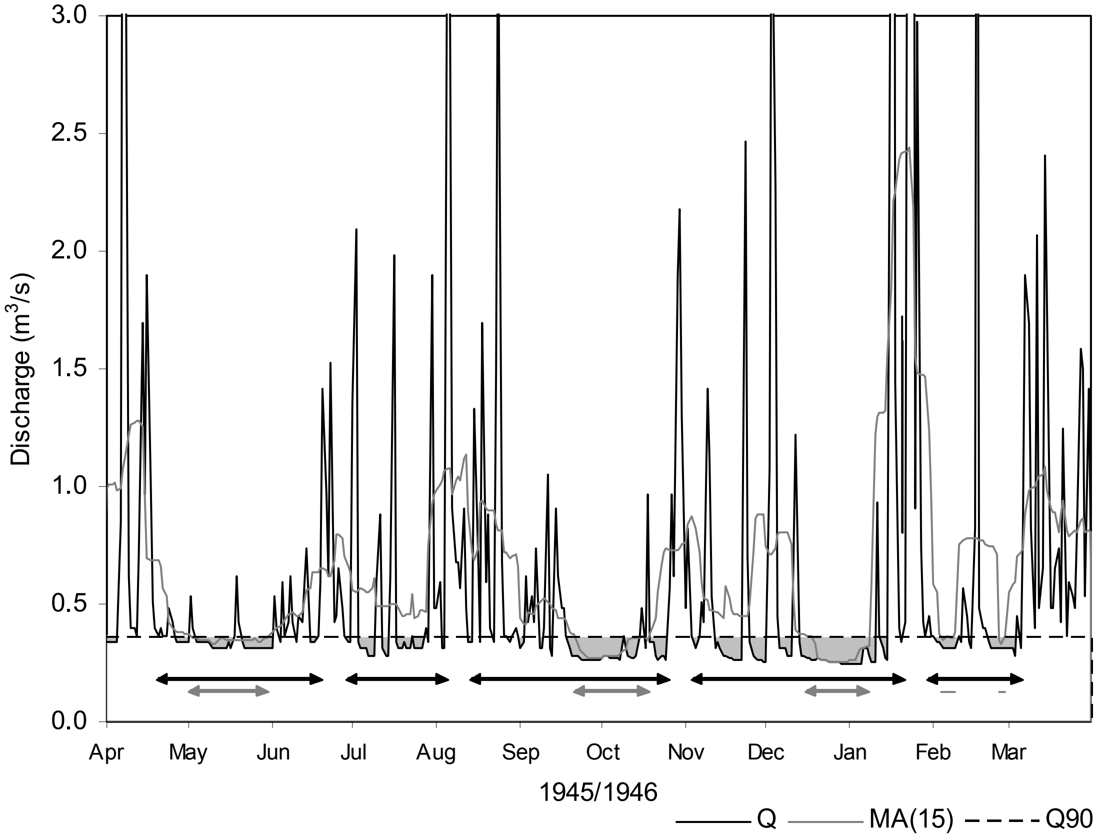


Figure 4.11 Illustration of how differently non-pooled drought events (shaded areas) were pooled by the IT-method with t_c = 5 days (upper arrows) and by a MA(15-day)-filter (lower arrows/lines).

The differences of a PDS for Honokohau Stream obtained by a MA(15-day)-filter and by an IT-method with t_c = 5 days are illustrated in Figure 4.11. The shaded areas indicate the deficit volumes of a non-pooled drought series and the arrows below show the drought periods as they were pooled by the 5-day-IT-method (upper arrows) and by the MA(15-day)-filter (lower arrows). It can be seen that by applying the MA(15-day)-filter less events are recorded and that the events which are recorded last much shorter than when the drought series is obtained by the 5-day-IT-method. For example from mid August 1945 to mid September 1945 a series of seven minor drought events, most of which last only one or two days are pooled with the IT-method, extending a succeeding larger drought event for a whole month. These minor droughts would not be pooled when the total pooled deficit volume would be calculated by subtracting the interevent excess volumes from the summed up deficit volumes, or be using an additional IV-criterion. Barely shortening the time of the IT-criterions would not suffice, since even the excess volumes of one or two-day long peaks vary considerably in size. Therefore it is recommended to consider the interevent excess volumes for flashy rivers in one way or another. The evaluation of the applicability of the MA(n-day)-filter is summarised in Table 4.7.

Table 4.7 Evaluation of applicability of the MA(n-day)-filter as pooling procedure for streams with different streamflow types

Streamflow type	Evaluation
Perennial	The MA(n-day)-filter can be optimised and used for all perennial streams and drought duration and deficit volumes can be compared. The method has here not been tested in detail, but it can be expected that a moving average interval of $n = 10$ days provides good results for non-flashy streams as suggested by Tallaksen et al. (1997) and as observed for Lindenborg. For the only flashy perennial stream in the global data set a MA(15-day)-filter could be recommended.
Perennial, seasonal	For the summer season the MA(n-day)-filter can be used in the same way as for perennial streams without frost influence. Important is how the summer droughts are selected, which is discussed in Section 4.6.2.
Intermittent	The MA(n-day)-filter has not been tested for intermittent streams. The suggestion is that during the *wet season* it can be used as for perennial streams and that during the *dry season* pooling is not necessary.
Ephemeral	Pooling is not relevant.

4.2.2.3 Global comparison

The MA(n-day)-filter is superior to the IT-method in the sense that all perennial streams can be compared no matter how their catchment characteristics and hydrographs look like. The value of n can easily be optimised. A disadvantage is, that the MA(n-day)-filter modifies the discharge series. Also drought durations of intermittent and perennial streams can be compared.

4.2.3 Sequent Peak Algorithm

4.2.3.1 Application of the Sequent Peak Algorithm

The Sequent Peak Algorithm (SPA) has been developed for reservoir design to derive the largest observed deficit volume. Here it is evaluated as pooling-procedure in connection with the threshold level method for the different streams. The same threshold levels were applied as for the calculations with the IT-method, for perennial streams $Q70$ and $Q90$ and for intermittent streams lower exceedance percentiles or the MQ, according to their percentage of zero-flow values.

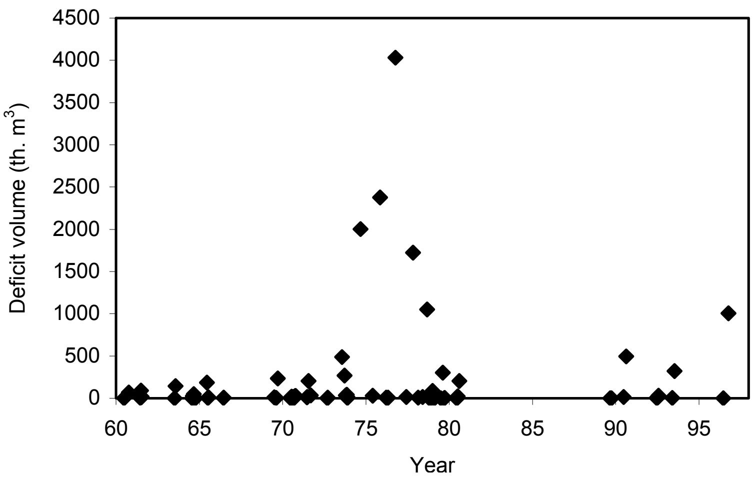


Figure 4.12 Drought events of Lindenborg at Lindenborg Bro, Denmark, characterised through the deficit volume, derived with the SPA and $Q_0 = Q90 = 1.67$ m^3/s.

When applying SPA as pooling-procedure for drought events derived from a discharge series of daily data, the problem can be that drought events that occur shortly after an major event get pooled to this event but are not accounted for in any way, neither the deficit volume of the major event increases nor its duration. In fact actually the period after the major event which is pooled to it is then considered to be a period without any drought events**.** The three graphs in Figure 4.13 show how the drought events within the 10-year period from March 1973 to February 1984 were observed for the river Lindenborg at Lindenborg Bro, Denmark for three different threshold levels. This is the period when the severest drought events during the whole data record occurred (Figure 4.12). At a threshold level of *Q*90 severe drought events were observed in each summer from 1973 to 1979. The 5 severest drought events in the data record were the ones from the summers 1976, 1975, 1974, 1977 and 1978 (in this order of severity). The major drought from 1973 was the 8th severest event and the one from 1979 the 10th severest. At a threshold level of $Q_0 = Q80$ the drought events from 1975, 1976 and 1977 are pooled to one major multi-year drought. The drought started in June 1975 and is considered to last until the highest deficit volume of the pooled event is reached. This is on October 13th 1976. The drought has then lasted for 517 days. In this way the event of 1977 is not considered in the total pooled drought duration and the year 1977 is rather considered to be a zero-drought year. But actually as the results from $Q_0 = Q90$ showed the fourth severest event occurred during that year. One therefore has to take special care that the threshold level is chosen low enough, so that no major multi-year drought events are recorded. For studying multi-year drought events a daily discharge series is usually not advisable and an annual discharge series is recommended. Of course the same problem can also happen for

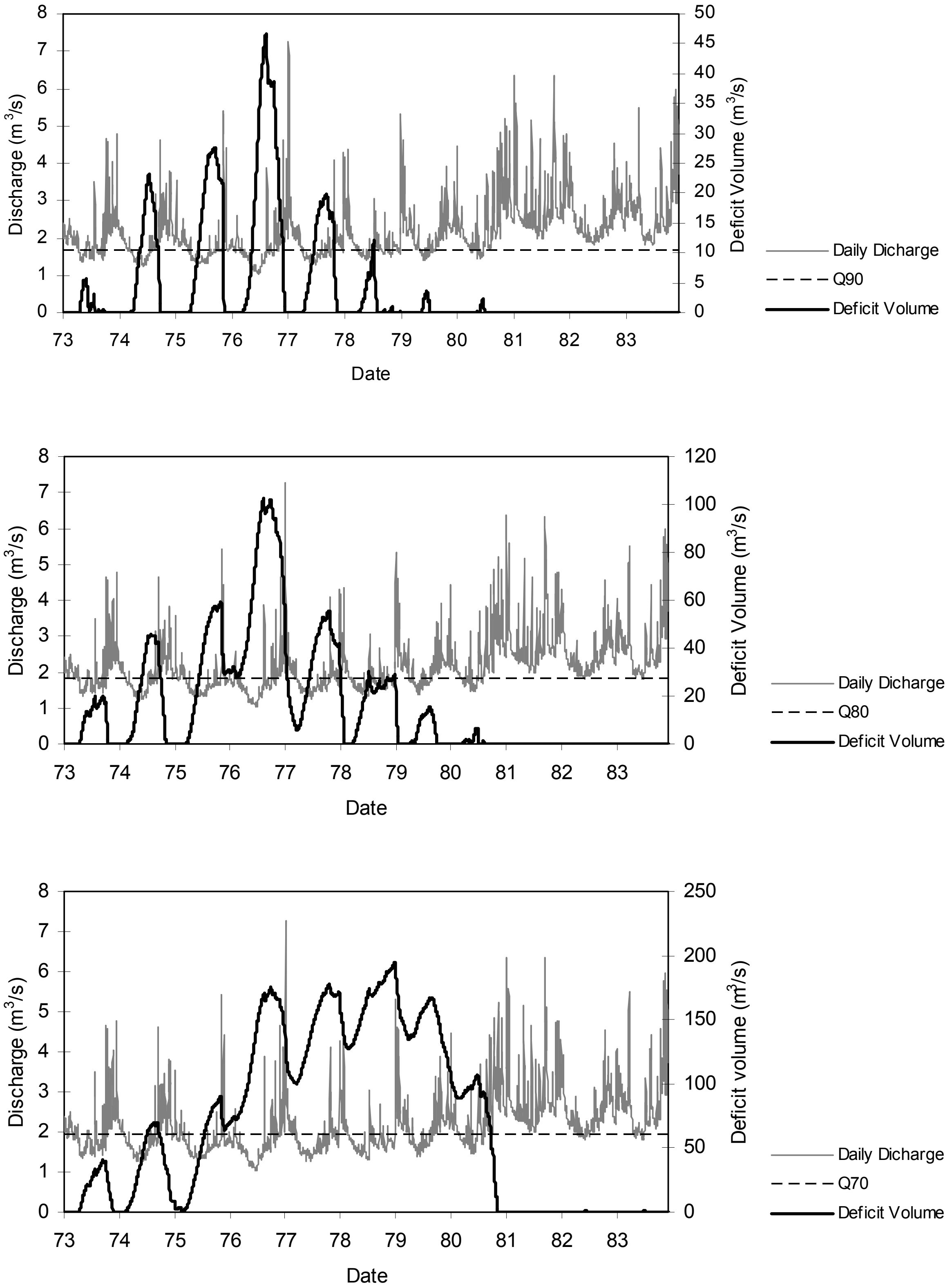


Figure 4.13 The deficit volume, w(t) in (m^3/s) derived by the SPA for the period 1973 to 1983 for the River Lindenborg, Lindenborg Bro, Denmark for three different threshold levels, Q_0. Upper: $Q_0 = Q90$. Middle: $Q_0 = Q80$. Lower: $Q_0 = Q70$.

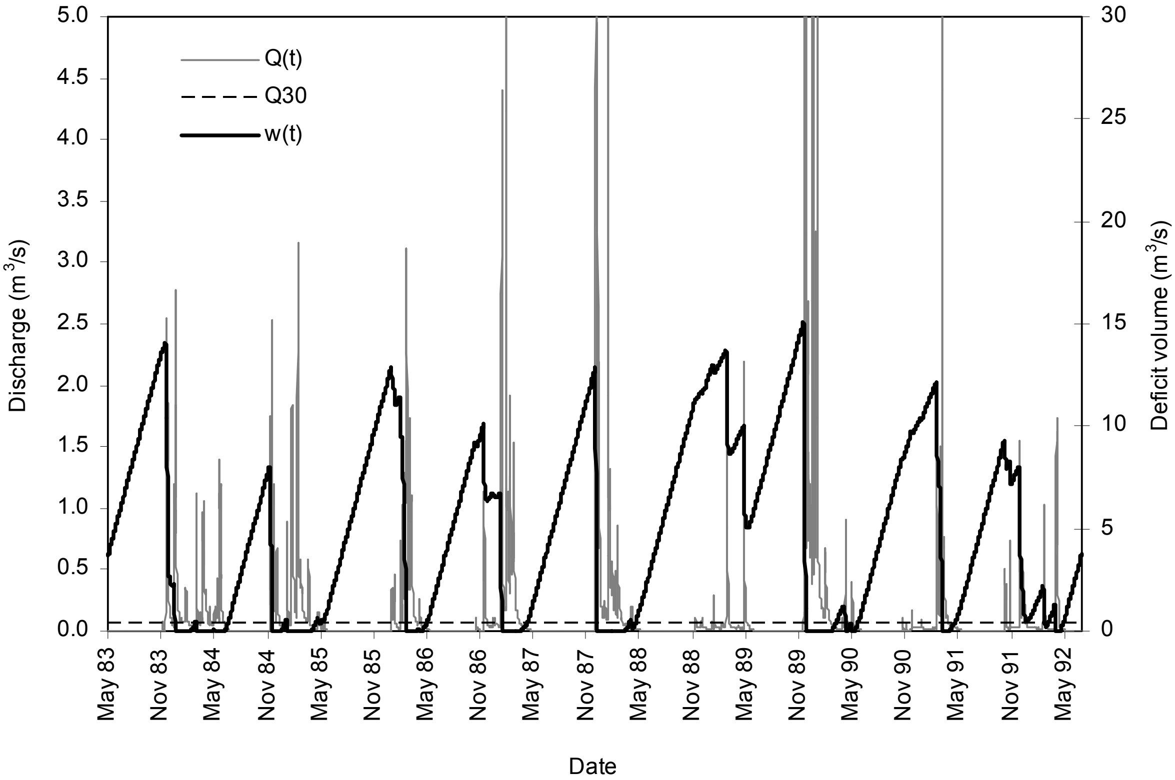


Figure 4.14 Discharge and deficit volume derived with the SPA of Sabar at Alfartanejo, Spain 1983-92, displaying how large deficit volumes of dry-season droughts can cause pooling of succeeding wet-season droughts.

within-year droughts, when two severe drought events occur within one year are pooled and the first one is only slightly more severe than the second one. For a frequency analysis it might therefore be favourable to apply an AMS-model rather than a PDS-model. In this way only one event is selected for each year anyway and the occurrence frequency is not influenced by not accounting for drought events pooled adjacently to a major event.

For intermittent streams the above described problem of recording periods after a major drought event as drought-free periods has the effect that wet-season droughts can not be observed properly on the basis of all-year data and that the deficit volumes of dry-season droughts are recorded instead. With a threshold level that is suitable for the wet-season, large deficit volumes might be derived during the dry season. Since then the daily time series of the deficit volume, $w(t)$ has not yet gone back to zero at the end of the dry season, the first part of the wet-season is recorded as drought-free period or a deficit volume belonging to a combined dry-and-wet-season drought is recorded. For example for the river Sabar at Alfartanejo, Spain the wet season lasts from November until May and a possible threshold level for the wet season is $Q30$. In Figure 4.14 it can be seen that for example during the wet-seasons 1985/86 and 1986/87 the deficit volume of the preceding dry-season drought is recorded but the wet-season droughts are unobserved and the period is thought to be drought-free. In the wet-season 1991/92 no deficit volume of a preceding dry-season drought is recorded, but almost the whole wet-season is recorded to be drought-free, even though the daily discharge is frequently below the threshold level. The whole wet-season of 1988/89 is part of a multi-year drought. The results of applying the SPA to streams with different streamflow types are summarised in Table 4.8.

Table 4.8 Evaluation of the applicability of the SPA as pooling-procedure for streams with different streamflow types

Streamflow type	**Evaluation**
Perennial	The SPA is an appropriate method when an AMS of drought events is to be selected, but not a PDS. To avoid multi-year droughts in the series often a low threshold level has to be chosen. Deficit volumes as well as drought durations of streams with different catchment and discharge characteristics can be compared.
Perennial, seasonal	Here summer droughts that extent into the winter season are always terminated at the end of the summer, which is not an optimal method to derive a series of only summer droughts. Possible methods to derive summer droughts are evaluated in Section 4.3.2.
Intermittent	*Wet season*: A seasonal calculation is necessary, either by predefining seasons and the use of only wet-season data or by identifying the season of each deficit period with $Q(t) > Q_0$ prior to pooling, since a threshold discharge which is suitable for the wet season might cause large deficit volumes during the dry season which causes droughts also in the wet season to be pooled and a deficit volume not belonging to the wet season is recorded. *Dry season*: Pooling is not relevant.
Ephemeral	Pooling is not relevant.

4.2.3.2 Global comparison

As a pooling-procedure the SPA can be recommended for the selection of AMS but not necessarily of PDS of all perennial streams as well as for intermittent streams but not to compare those streams, since the pooling criteria is based on the deficit volume, which is not comparable when zero-flow periods occur.

4.3 Comparison: IT-method and SPA

4.3.1 General comparison

The results from the IT-method and from the SPA are compared only for a threshold level of $Q_0 = Q90$ for perennial streams, since the application of the SPA as pooling-procedure seemed not advisable in general for a threshold level of $Q70$ because of the frequent occurrence of multi-year droughts. For intermittent streams higher threshold levels were chosen. Minor droughts are defined according to the two criteria to remove minor droughts, introduced in Section 2.3.1 α and d_{min} with $\alpha = 0.005$ and $d_{min} = 3$ days (for the parameter choice see Section 4.4.1.2). Compared are the numbers of droughts, minor droughts and multi-year droughts and the percentage of zero-drought years (Table 4.9) as well as mean drought duration with and without minor droughts, the maximum duration and the mean duration of the 10 longest events (Table 4.10). The deficit volumes derived by the SPA are not directly comparable to those derived by the IT-method, since with the SPA the interevent excess volumes are subtracted from the total pooled deficit volume, whereas in the IT-method they are ignored (Table 4.11).

Table 4.9 Comparison of the results from the IT-method and the SPA for the global data set with $Q_0 = Q90$ if not stated otherwise, in terms of number of droughts, minor droughts and multi-year droughts as well as the percentage of zero-drought years

Stream	Droughts		Minor droughts		Percentage of zero-drought years (%)		Multi-year droughts	
	IT	SPA	IT	SPA	IT	SPA	IT	SPA
Pecos River	101	143	52	62	26.5	17.6	0	0
Elandriverie	22	21	6	7	25.0	25.0	0	0
Bagamati River	23	23	1	1	45.5	45.5	0	0
Sabar (*MQ*)	91[1]	14[1]	18[1]	5[1]	0.0[1]	72.4[1]	2[1]	2[1]
Arroyo Seco (*Q*70)	79[1]	63[1]	9[1]	6[1]	14.7[1]	16.2[1]	0[1]	1[1]
Ray (*Q*50)	94[1]	103[1]	28[1]	33[1]	24.2[1]	0.0[1]	1[1]	1[1]
Lambourn	25	41	12	30	66.7	61.1	1	1
Lindenborg	66	80	31	51	37.8	37.8	0	0
Ngaruroro	79	96	13	28	9.4	9.4	0	0
Hurunui	69	73	32	38	25.0	25.0	0	0
Lågen	69	70	13	13	46.4	41.7	0	0
Inva	46	114	0	52	50.9	40.0	0	0
Rhine (Y)	128	103	29	29	37.0	37.0	0	0
Rhine (S)	86	85	14	20	43.5	38.0	0	0
Ostri	35	42	2	6	26.5	11.8	0	0

[1] a different threshold level is used, as stated with the stream in the first column.

When minor droughts are excluded the number of derived drought events by the two different methods is very similar for most streams and in general the SPA returns more minor droughts than the IT-method. An exception is Sabar, where much less droughts are returned with the SPA than with the IT-method, since with the SPA many drought events are pooled to one major multi-year drought, lasting for 5.5 years. The only other stream for which the IT-method returns more minor droughts than the SPA is Arroyo Seco, also due to a multi-year drought.

The percentage of zero-drought years can differ only for the frost influenced streams, due to the different ways of selecting summer droughts represented by the IT-method and the SPA, and for streams experiencing multi-year droughts. Multi-year droughts are counted as one drought in one year, so the other years belonging to the multi-year drought are counted as zero-drought years.

When a low threshold level is chosen, as the $Q90$ for perennial streams, the number of multi-year droughts is the same for both pooling-procedures, otherwise more or longer multi-year droughts are obtained with the SPA, as here for Sabar ($Q_0 = MQ$) and Arroyo Seco ($Q_0 = Q70$) and in the results with $Q_0 = Q70$ (see Appendix 3 for the results from the IT-method and Appendix 4 for the results from the SPA.

The mean duration of all events is in some cases higher for the SPA-PDS and in some cases for the PDS by the IT-method. This does not vary according to the different types of regimes but it rather varies also for streams with the same type of regime. In general, the mean durations derived by the two pooling procedures are very similar, in particular when minor droughts are excluded, except for Sabar, due to the long multi-year drought, as well as for Inva. For Inva several shorter droughts are more frequently pooled with the IT-method than with the SPA, since low flow periods can be interrupted by short interevent periods with a large excess volume. This causes also the difference in the maximal drought duration, 97 days with the IT-method in 1953 and 77 days with the SPA in 1954. In 1953 an event of 61 days is pooled with the SPA (Figure 4.15).

Table 4.10 Comparison of the results from the IT-method and the SPA for the global data set with $Q_0 = Q90$ if not stated otherwise, in terms of mean duration with and without minor droughts, maximal duration and mean duration of the 10 longest droughts

Stream	Mean duration (days)		Mean duration without minor droughts (days)		Maximal duration (days)		Mean duration of the 10 longest droughts (days)	
	IT	SPA	IT	SPA	IT	SPA	IT	SPA
Pecos River	16	14	28	22	300	169	72	72
Elandriverie	21	22	28	32	107	189	42	44
Bagamati River	44	33	46	38	170	163	84	66
Sabar (*MQ*)	95[1]	270[1]	118[1]	418[1]	387[1]	2004[1]	330[1]	377[1]
Arroyo Seco (*Q*70)	94[1]	117[1]	106[1]	129[1]	269[1]	556[1]	199[1]	231[1]
Ray (*Q*50)	55[1]	45[1]	76[1]	65[1]	525[1]	499[1]	245[1]	231[1]
Lambourn	58	33	105	115	403	393	132	126
Lindenborg	24	17	41	43	173	161	100	95
Ngaruroro	17	12	19	17	90	90	51	51
Hurunui	15	13	25	25	136	136	55	56
Lågen	13	13	15	16	54	54	37	38
Inva	26	9	26	16	97	77	69	53
Rhine (Y)	27	35	34	47	153	309	104	158
Rhine (S)	31	31	36	39	153	274	102	124
Ostri	10	8	10	9	35	35	21	19

[1] a different threshold level is used, as stated with the stream in the first column.

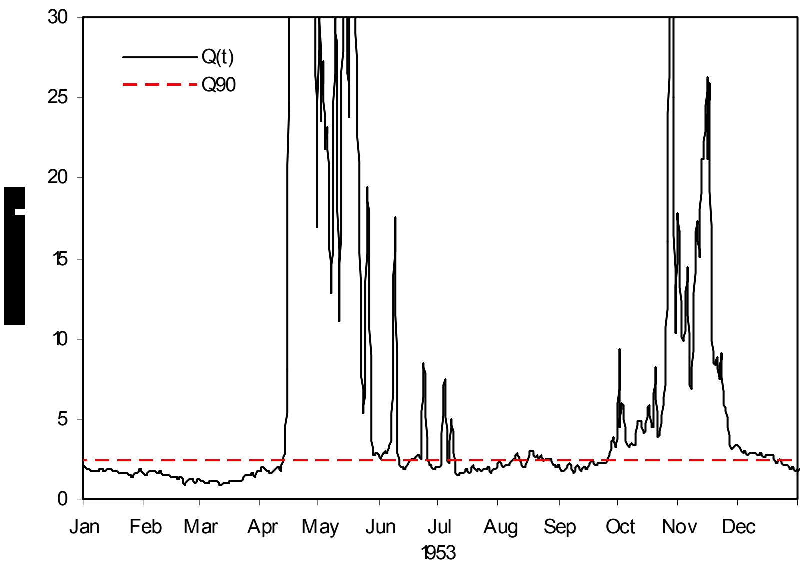


Figure 4.15 The year with the longest drought event as derived with the IT-method at Inva at Kudymkar, Russia, lasting from June 12th until September 16th (SPA: July 8th – September 6th).

The maximum duration derived with the two pooling-procedures is the same in the cases of Ngaruroro, Hurunui, Lågen and Ostri, in each case also the same event represents the maximum. For Ngaruroro and Hurunui even the four largest events are the same, only slightly deviating in the derived durations. Also for Bagamati River, Ray, Lambourn and Lindenborg the maximum durations derived with the IT-method and the SPA deviate only little. In all cases the maximum duration derived with the IT-method is larger. This is because at the beginning of a low flow period, small droughts are more frequently pooled with the IT-method, when they are interrupted only by a short interevent period, since their deficit volumes are small. Larger differences are again observed for Sabar and Arroyo Seco, due to the multi-year droughts, and Inva, as well as for Pecos River, Elandriverie and Rhine. For Pecos River only summer droughts should be considered. The largest event returned by the IT-method included a whole winter season (Section 4.3.2.2) and is therefore much larger than the one returned by the SPA. For Elandriverie and Rhine the maximal duration is much larger when pooling is done with the SPA. This happens when the discharge rises above the threshold level for more than 5 days in the middle of a long low flow period, since then the interevent excess volume is frequently smaller than the preceding deficit volume. Examples are given in Figure 4.16 for Elandriverie and Figure 4.17 for Rhine, each displaying the year with the longest drought as derived with the SPA.

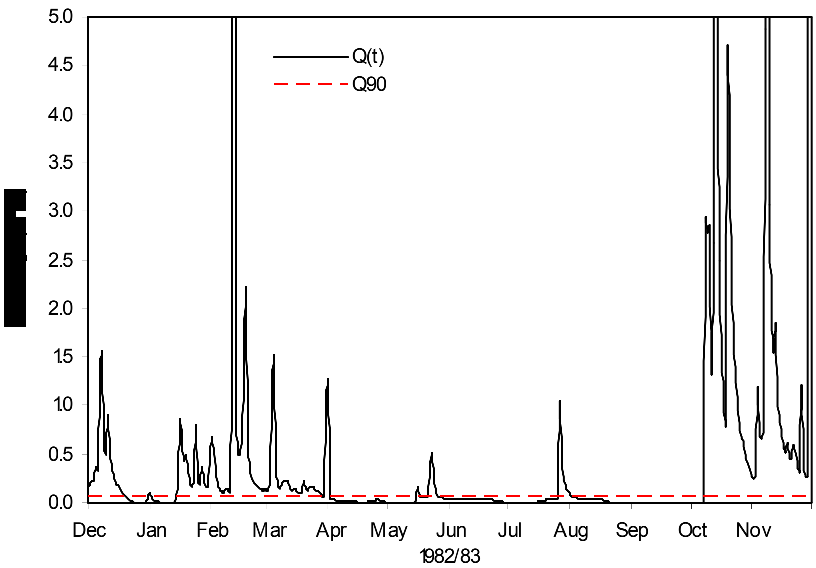


Figure 4.16 Daily discharge for Elandriverie from December 1982 until November 1983 showing periods of discharge above the threshold level longer than 5 days but with small excess volumes within a long low flow period, causing different pooling by the IT-method and the SPA.

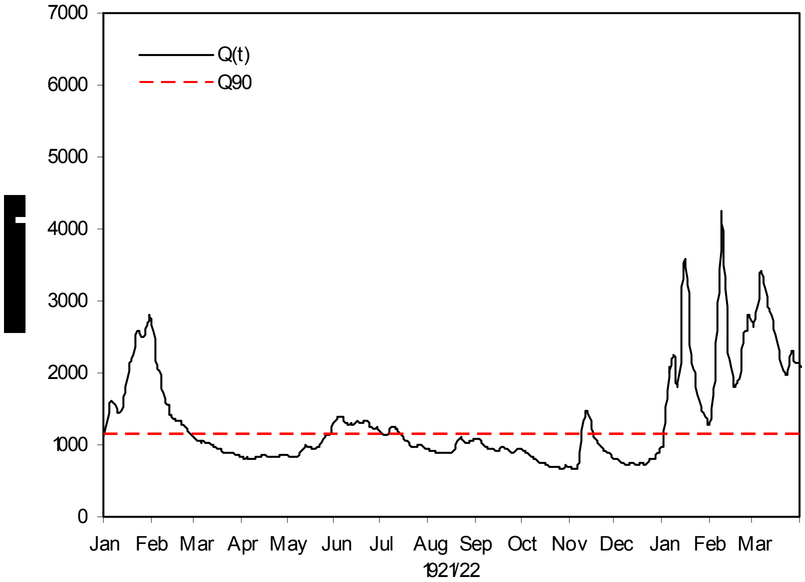


Figure 4.17 Daily discharge for Rhine from January 1921 until March 1922 showing a period of discharge above the threshold level longer than 5 days but with a small excess volume within a long low flow period, causing different pooling by the IT-method and the SPA.

Table 4.11 Comparison of the results from the IT-method and the SPA for the global data set with $Q_0 = Q90$ if not stated otherwise, in terms of mean deficit volume with and without minor droughts, maximal deficit volume and mean deficit volume of the 10 severest droughts

Stream	Mean deficit volume (10^3 m^3)		Mean deficit volume without minor droughts (10^3 m^3)		Maximal deficit volume (10^3 m^3)		Mean deficit volume of the 10 severest droughts (10^3 m^3)	
	IT	SPA	IT	SPA	IT	SPA	IT	SPA
Pecos River	171	159	339	275	8485	4666	1218	1220
Elandriverie	66	50	90	73	424	395	142	102
Bagamati River	146	124	152	142	807	796	297	260
Sabar (*MQ*)	1260[1]	2199[1]	1568[1]	3411[1]	5370[1]	8442[1]	4633[1]	3074[1]
Arroyo Seco (*Q70*)	1300[1]	1651[1]	1467[1]	1824[1]	3896[1]	4211[1]	3178[1]	3317[1]
Ray (*Q50*)	39[1]	31[1]	55[1]	46[1]	440[1]	410[1]	190[1]	172[1]
Lambourn	527	308	1008	1140	3934	3917	1302	1252
Lindenborg	255	200	475	538	4056	4031	1398	1380
Ngaruroro	1158	879	1382	1234	10676	10635	5475	5357
Hurunui	4867	4517	8961	9270	98751	98751	26897	27035
Lågen	3076	3657	3766	4546	33757	33757	11821	15275
Inva	990	361	990	645	6823	5753	3376	2693
Rhine (Y)	381530	433170	491264	600411	4324320	4618512	2322259	2628323
Rhine (S)	432232	392619	515039	512002	4192128	4148496	2188391	2059500
Ostri	1483	1342	1571	1552	7182	7182	3871	4014

[1] a different threshold level is used, as stated with the stream in the first column.

As said before, the deficit volumes derived with the IT-method and the SPA can not be directly compared, because of the different ways of calculating them. However, it can be seen in Table 4.11 that the maximal observed deficit volumes returned by the two methods are very similar or even identical in the cases when also the maximal duration is similar. They are identical for Hurunui, Lågen and Ostri and very similar for Bagamati River, Lambourn and Lindenborg. This suggests that for the derivation of the severest events the way of calculating the deficit volume is of minor importance, whereas the results for all deficit characteristics can differ considerably depending on the applied pooling-procedure.

For Honokohau Stream the SPA is compared to the MA(15-day)-filter instead of to the IT-method, since for Honokohau Stream the IT-method was not considered to be appropriate. These two methods are also compared for the river Lindenborg. For the river Lindenborg the MA(10-day)filter was applied. Since with the MA(*n*-day)-filter also the interevent excess volume is considered as it is in SPA, also the deficit volumes can be directly compared.

For both streams less drought events are derived with the MA(*n*-day) filter than with the SPA, since the MA(*n*-day)-filter removes minor droughts more effectively through the smoothing of the discharge curve (Table 4.12). Consequently, a higher number of zero-drought years is received with the MA(*n*-day)-filter. But also when minor droughts are excluded from the PDS derived with the SPA for Honokohau Stream, still a lot more droughts remain than with the MA(*n*-day)-filter. As a consequence the mean values of both deficit characteristics with and without minor droughts are much smaller for the SPA-PDS of Honokohau Stream (Table 4.13). For Lindenborg they are as well smaller for the SPA-PDS, but the difference is not as big.

The maximal duration and deficit volume as well as the mean of the ten longest/severest events is very similar for Lindenborg, with the duration derived with the MA(*n*-day)-filter being slighter larger and the deficit volume slightly smaller as compared to the results from the SPA (Table 4.13 and Table 4.14). But the two methods derived the same ten events as the most severest/longest ones in the same order and in each case with very similar magnitude. For Honokohau Stream also the maximum values are larger for the MA(*n*-day)-filter as compared to the SPA, while some of the severest events were derived with larger durations and deficit volumes with the MA(*n*-day)-filter others with the SPA. A big difference is in the maximal deficit volume. This is again, since more succeeding drought events are pooled with the MA(n-day)-filter than with the SPA, and the same events start later and earlier terminated with the SPA.

Table 4.12 Comparison of the results from the MA(n-day)-filter and the SPA for Honokohau Stream with n = 15 days and for Lindenborg with n = 10 days in terms of the number of drought, minor droughts and multi-year droughts as well as percentage of zero-drought years

Stream	Droughts		Minor droughts		Maximum of droughts in one year		Percentage of zero-drought years (%)		Multi-year droughts	
	MA	SPA	MA	SPA	MA	SPA	MA	SPA	MA	SPA
Honokohau Stream	33	290	3	202	5	28	69.8	49.1	0	0
Lindenborg	40	80	14	51	5	9	45.9	37.8	0	0

Table 4.13 Comparison of the results from the MA(n-day)-filter and the SPA for Honokohau Stream with n = 15 days and for Lindenborg with n = 10 days in terms of mean duration with and without minor droughts, maximal duration and mean duration of the 10 longest droughts

Stream	Mean duration (days)		Mean duration without minor droughts (days)		Maximal duration (days)		Mean duration of the 10 longest droughts (days)	
	MA	SPA	MA	SPA	MA	SPA	MA	SPA
Honokohau Stream	17	5	19	10	64	61	37	31
Lindenborg	42	17	54	43	168	161	97	95

Table 4.14 Comparison of the results from the MA(n-day)-filter and the SPA for Honokohau Stream with n = 15 days and for Lindenborg with n = 10 days in terms of mean deficit volume with and without minor droughts, maximal deficit volume and mean deficit volume of the 10 severest droughts

Stream	Mean deficit volume (10^3 m^3)		Mean deficit volume without minor droughts (10^3 m^3)		Maximal deficit volume (10^3 m^3)		Mean deficit volume of the 10 severest droughts (10^3 m^3)	
	MA	SPA	MA	SPA	MA	SPA	MA	SPA
Honokohau Stream	55	9	61	29	281	188	143	121
Lindenborg	493	200	669	538	3999	4031	1349	1380

The MA(15-day)-filter seems to be the more appropriate pooling-procedure than the SPA for streams like Honokohau Stream, who show a high daily variability also during low flow periods and a relative low annual variability. For these streams short periods below the threshold level are natural due to the flashiness of the streams and do not have any major effects. It therefore seems more logical to define periods when the fluctuations take place on a lower than normal level as drought events, rather than the periods when the discharge is below the threshold level. Therefore a smoothing filter which averages over longer periods as it does the MA(15-day)-filter seems to be an appropriate method to derive drought events.

A general advantage of the SPA is that in contrast to the IT-method and the MA(*n*-day)-filter no further parameters have to be chosen besides the threshold level. This makes the results from different perennial streams more comparable. For intermittent streams on the other hand this is not true, since the major factor deciding whether drought events are pooled is the deficit volume. But as it was explained before the deficit volume can not be calculated in a way that allows comparisons when zero-flow values occur and when the streams experience a different percentage of zero-flow values.

4.3.2 Way to calculate seasonal droughts

4.3.2.1 Cold or temperate, no dry season

The two pooling-procedures, IT-method and SPA, represent two different ways to select only summer drought events from a discharge series, both use predefined seasons, but in the way represented by the SPA the seasons are completely fixed and summer droughts are always terminated the latest at the end of the summer, whereas the way represented by the IT-method is more flexible. The streams experiencing a frost season within a cold or temperate climate region are Hurunui in New Zealand, Lågen and Ostri in Norway, Inva in Russia, and Rhine at Lobith, the Netherlands.

The comparison of the PDS derived by the two methods showed that in the SPA-PDS the severest events ended on the last day of the summer season, whereas in the corresponding IT-PDS they lasted up to three weeks into the winter season or ended up to two weeks earlier. Especially for a frequency analysis cut off events as well as mixed events (a summer drought that turns into a winter drought) are unfavourable, since they harm the assumption of an iid drought sample. The SPA-PDS also included many short events lasting up to eight days which were either somewhat longer in the IT-PDS, continuing into the winter season, or, as in most cases, they were not included in the IT-PDS at all, since they were part of a longer winter drought. With the IT-method, on the other hand, it can happen that when a very severe summer drought turns into a winter drought and then continues the whole winter season, no part of it is recognised as summer drought and the whole summer is recorded as if no drought has occurred at all. For example the second severest event as observed with SPA of the river Lågen at Rosten, Norway as well as the second severest drought event of the river Ostri at

Liavatn, Norway were not recorded at all in the summer IT-PDS, since they continued throughout the whole winter.

In general it can be said that for drought calculations in frost affected catchments the more flexible way as represented by the IT-method is more advisable, since it does not include any incomplete summer drought events or parts of winter droughts. Also the risk of returning mixed summer-and winter-droughts is smaller. Therefore it is recommended to derive a PDS of summer drought events always in several steps, no matter which pooling-procedure is applied. The steps are to first derive a series of periods with $Q(t) < Q_0$ for the whole year, then classify those periods as either summer events or winter events, and as the last step the pooling of the summer events is conducted. The first series of all-year data should be checked for severe summer-drought events that turn into an even longer winter-drought and are therefore not included in the final summer-PDS. The remaining problem is, in which way these events should be included in the summer-PDS. This procedure can also be used when the SPA-pooling-procedure is applied as long as it is not requested that $w(t)$ returns to zero already at the beginning of the winter and the maximum of this last period of $w(t)$ being greater than zero is chosen as drought event anyway.

How well this method performs as compared to one using additional information from temperature series is still to be evaluated. And in order to find out how high the error of wrong summer drought identification even more detailed information is needed. Besides temperature data one has to know about the processes taking place in the catchment, e.g. how long the time lag is between a precipitation deficit and a streamflow drought and how fast the discharge does respond to the first frost days and the first days when snowmelt occurs.

4.3.2.2 Winter dry climate

Pecos River in the USA lies within a winter dry climate region. Because of the missing discharge peak at the end of the winter in a winter-dry climate it can also happen that drought events start during the summer season, continue throughout the whole winter and then also continue into the next summer. When more than half of the drought's days belong to either of two summer seasons, the whole drought is still considered as summer drought by the flexible summer-drought-identification method implemented with the IT-method. At Pecos River one such mixed drought event was included in the PDS of summer droughts for a threshold level of $Q_0 = Q90$, at $Q_0 = Q70$ it were two drought events. These events were no multi-year events, since they took place between two succeeding rainy periods and lasted less than a year.

For frost influenced streams with a winter-dry climate it might be better to base a drought study only on the wet season rather than the summer season, when the wet season is shorter than the summer season. For Pecos River the wet season lasts from May until October and thus starts two months and ends one month earlier later than the summer season. When also dry-season droughts are to be studied, one might want to consider using annual data instead of daily data.

4.4 Frequency analysis with NIZOWKA2003

When testing the applicability of the frequency analysis included in NIZOWKA2003, which follows Zelenhasić & Salvai (1987), two parts are evaluated: (a) is the method itself applicable for streams of all types of hydrological regimes? (b) Can the GP-model be recommended as distribution model for $H_t(x)$ (distribution function of all drought events, expressed as deficit volume or duration, within the time interval $[0, t]$) and the Poisson-model as distribution model for $\Pr(Z_t = k)$ (the probability that k drought events occur during the time interval $[0, t]$)?

The first question covers several aspects: (a.1) Can a suitable distribution function be fitted to the sample and does it also fit well in the extreme end of the observed sample? (a.2) Does the presence of a high number of zero-drought years disturb the estimation? (a.3) Does the choice of threshold level influence the estimation? (a.4) What happens when multi-year droughts are present?

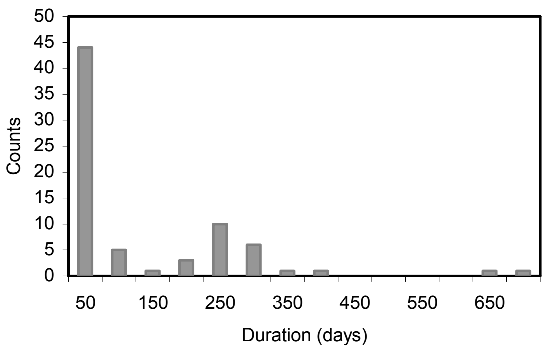
4.4.1 Preparatory steps

Before conducting the frequency analysis it has to be assure that each PDS consists only of extreme drought events and that the events are identically and independently distributed. The drought events are assumed mutually independent following the application of the IT-method as pooling-procedure. That the events are identically distributed means that they all have to belong to the same population, which can in most cases be checked by looking at the histograms of the drought events. The separation of different drought event populations is discussed in the following section. For intermittent streams one additionally has to consider how the zero-flow values influence the calculation of deficit volumes (Section 3.2.2.4). A PDS of extreme events can be derived by excluding all minor droughts. The choosing of appropriate values for the criteria to remove minor drought events, α and d_{min} is discussed as second preparatory step for a frequency analysis in Section 4.4.1.2.

4.4.1.1 Separation of different drought event populations

The histograms of the deficit volumes and durations showed that for the global data set only the PDS of intermittent streams contained events from two or even more populations. This was observed for all of the used intermittent streams except for Elands River. In NIZOWKA2003 no method is available to fit a two-component distribution to the PDS, therefore it is necessary to separate the drought events and to conduct a frequency analysis for each of the populations separately. As discussed in Section 3.2.2.2 the following options exist within NIZOWKA2003: (a) selecting events of only one season, (b) choosing a high value for d_{min} or (c) using a lower discharge value as threshold level.

For the river Ray at Grendon Underwood, UK a PDS of one population was chosen by using a new threshold level instead of a $MQ = 0.097$ m^3/s. Now a threshold level equal to $Q50 = 0.011$ m^3/s was used (Figure 4.18). By choosing a high enough value for d_{min} to separate the different populations in the PDS with an threshold level equal to MQ, $\Pr(Z_t = k)$ could not be estimated as only one year with more than one drought occurred. For the river Sabar at Alfartanejo, Spain this could be achieved by setting $d_{min} = 200$ days, which also excludes some small dry-season droughts (Figure 3.23). One has to keep in mind that d_{min} refers to the real drought duration, i.e. the actual number of days with a discharge below the threshold level, while the drought duration plotted in the histogram shows the full drought duration of the pooled events. Therefore for the drought duration above which only events belonging to the population of the severest events are observed the corresponding actual number of days with a discharge below the threshold level has to be found.



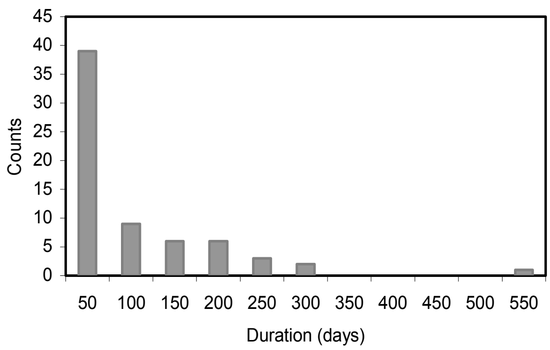


Figure 4.18 Histograms of drought duration of Ray at Grendon Underwood, UK for two different threshold levels, Q_0, one showing two different drought populations, the other one only one. Left: $Q_0 = MQ = 0.097$ m^3/s. Right: $Q_0 = Q50 = 0.011$ m^3/s.

From the histograms of drought durations from Arroyo Seco at Soledad, USA it can neither be decided how many different populations the observed drought event series consists of nor can the events of only one population be easily selected (Figure 4.19). Therefore no frequency analysis was performed for Arroyo Seco.

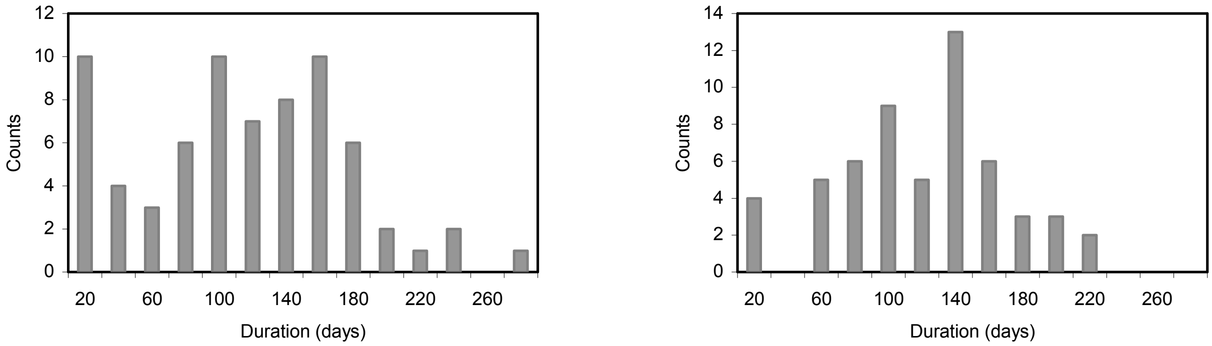


Figure 4.19 Histograms of drought duration of Arroyo Seco at Soledad, USA for two threshold levels, showing several drought populations. Left: $Q_0 = Q70 = 0.226$ m^3/s. Right: $Q_0 = Q75 = 0.142$ m^3/s.

4.4.1.2 Exclusion of minor droughts

When conducting a frequency analysis, the results of the estimation depend also on the criteria for removing minor drought events, here α and d_{min}, as well as on the chosen distribution model. Here the method to estimate *T*-year events developed by Zelenhasić & Salvai (1987) is used for the frequency analysis, and the theoretically most correct combination of a Poisson distribution model for $\Pr(Z_t = k)$ (the probability that k drought events occur during the time interval $[0, t]$) and a Generalized Pareto (GP) distribution model for $H_t(x)$ (distribution function of all drought events (expressed as deficit volume or duration) within the time interval $[0, t]$) is to be evaluated in comparison to other extreme value distribution models. Therefore the search for a good combination of α and d_{min} is based on the goodness-of-fit as well as the results of fitted distribution functions of different models, with special focus on the Poisson-GP combination.

The *goodness-of-fit* of the different distribution functions was evaluated through the attained significance level, ρ obtained by the χ^2-goodness-of-fit test (Section 2.3.3). The attained significance level is the smallest significance level, α for which the null-hypothesis would be rejected, given the observed value of the test statistic, T. The null-hypothesis states, that the observed sample comes from a given theoretical distribution model. The smaller the value of ρ, the stronger is the evidence against the null-hypothesis. The χ^2-goodness-of-fit test does not enable one to find the 'best' or 'true' distribution model for a population of an unknown probability distribution (Stedinger et al., 1993), but it allows to decide, which of the fitted distributions models perform reasonably well. So the χ^2-goodness-of-fit test can be used to find out whether the GP model could be appropriate and in case it is not, how the other distribution models adapt.

Often the fitted distribution functions model the sample well in the middle range of the observed events, were the sample density is high, but less well or poorly in the range of the severest events. Therefore the goodness-of-fit of the different distribution functions in the extreme range was judged separately by visual inspection.

The *50-year event* is chosen for comparison of the results obtained by different distribution functions. The extreme events are often estimated with high uncertainty, since only few observations of extreme events are available to fit a theoretical distribution model to the observations. According to Haan (1977) it can generally be recommended, that the return periods of events (in years) should not be extrapolated to more than twice the number of observed events, in order to still keep a satisfactory level of certainty. For most of the used data records a number of at least 25 observed events can be expected and therefore the 50-year event can be estimated.

Here the nine combinations of $\alpha = 0.000$, 0.005 or 0.010 and $d_{min} = 1$, 3 or 5 days were compared. For the combination of $\alpha = 0.000$ and $d_{min} = 1$ day it was only possible to conduct an estimation for the river Lindenborg but not for any other stream from the global data set. The comparison is made for the same selection of perennial rivers as used for the optimisation of the IT-criterion, which are the rivers Lindenborg, Ngaruroro, Bagamati River and Honokohau Stream. The intermittent streams could not be used, since their PDS consisted of drought events belonging to different populations. Again a threshold level of $Q_0 = Q90$ was applied. Mutually dependent droughts are pooled prior to removing minor events using the IT-method for the rivers Lindenborg, Ngaruroro and Bagamati River and with a MA(15-day)-filter for Honokohau Stream.

For most streams different combinations of α and d_{min} provided identical PDS and thus identical estimations for the 50-year event (Table 4.15). The use of only d_{min} did not allow to fit a distribution model satisfyingly well with NIZOWKA2003 for any of the tested d_{min}-values. It was concluded that the two parameters α and d_{min} have different importance for different streams and that it is advisable to use a combination of both and the options of $\alpha = 0.000$ as well as $d_{min} = 1$ day are rejected.

Table 4.15 Relative deficit volumes of the 50-year event from estimations with different values of α and d_{min} and a fitted GP distribution for different streams. Upper left: Lindenborg. Upper Right: Ngaruroro. Lower Left: Bagamati River

Lindenborg

d_{min} \ α	0	0.005	0.01
1	186.13	22.22	18.47
3	37.84	22.22	18.47
5	26.37	20.36	18.06

Ngaruroro

d_{min} \ α	0	0.005	0.01
1	-	10.3	8.41
3	11.8	10.3	8.65
5	8.99	8.99	8.14

Bagamati River

d_{min} \ α	0	0.005	0.01
1	-	10.81	10.81
3	-	10.81	10.81
5	-	9.31	9.31

The exclusion of minor droughts can increase the number of zero-drought years to an unfavourable extent, since a high number of zero-drought years can make it impossible to accomplish a good estimation. Here the number of zero-drought years stayed the same for all three α-values and all values of d_{min} for Bagamati River, but increased 8 % for Lindenborg for $\alpha = 0.005$ or 0.010 or $d_{min} = 3$ or 5 days as compared to $\alpha = 0.000$ and $d_{min} = 1$ day, and 3 % for Ngaruroro when α was set to 0.010 or d_{min} to 5 days. This is one reason against the higher parameter-values. Also in the case of an outlier in the extreme part of the severe events it is favourable to apply a smaller value for α, since then less non-minor drought events are omitted.

On the example of the Generalized Pareto model the fitted distribution functions for different combinations of α and d_{min} are presented in Figure 4.20 for Lindenborg, in Figure 4.21 for Bagamati River and in Figure 4.22 for Ngaruroro. However, higher parameter-values resulted in distribution functions with better overall fit for all streams. At the same time they gave lower estimates of the 50-year event (Table 4.15) and the same distribution model fitted in the extreme range either better or equally well for $\alpha = 0.005$ as compared to $\alpha = 0.010$. Therefore the combination of $\alpha = 0.005$ and $d_{min} = 3$ days was considered to be the best choice, when applying the IT-method as pooling-procedure.

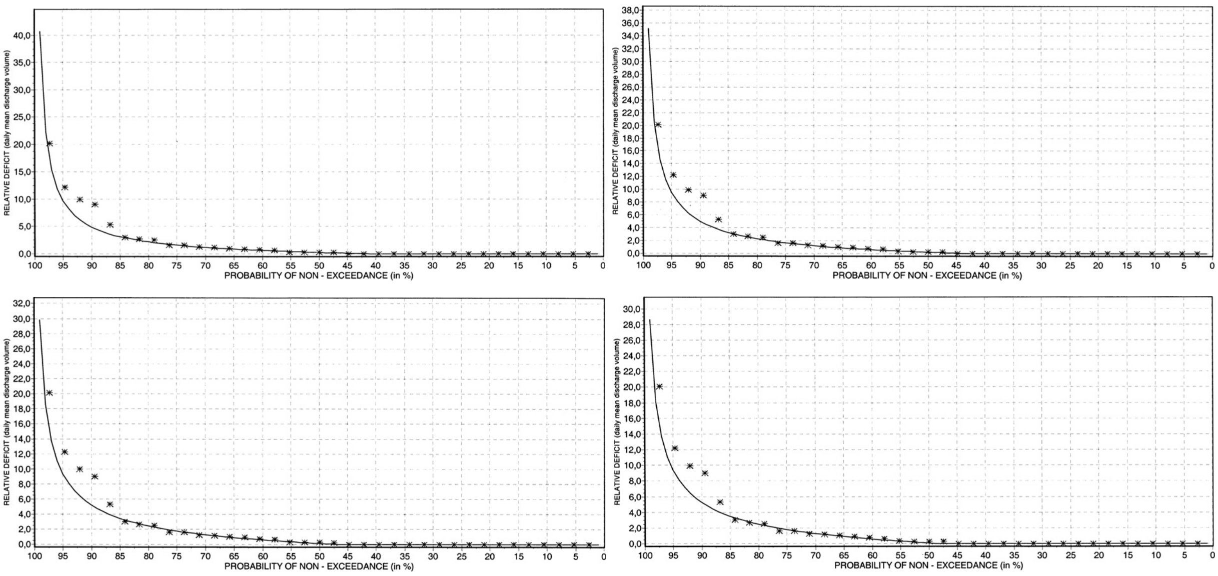


Figure 4.20 Fitted GP distribution functions for Lindenborg with different values for α and d_{min}. Upper left: $\alpha = 0.005$, $d_{min} = 1$ day ($\alpha = 0.005$, $d_{min} = 3$ days is identical). Upper right: $\alpha = 0.005$, $d_{min} = 5$ days. Lower left: $\alpha = 0.010$, $d_{min} = 1$ day ($\alpha = 0.005$, $d_{min} = 3$ days is identical). Lower right: $\alpha = 0.010$, $d_{min} = 5$ days.

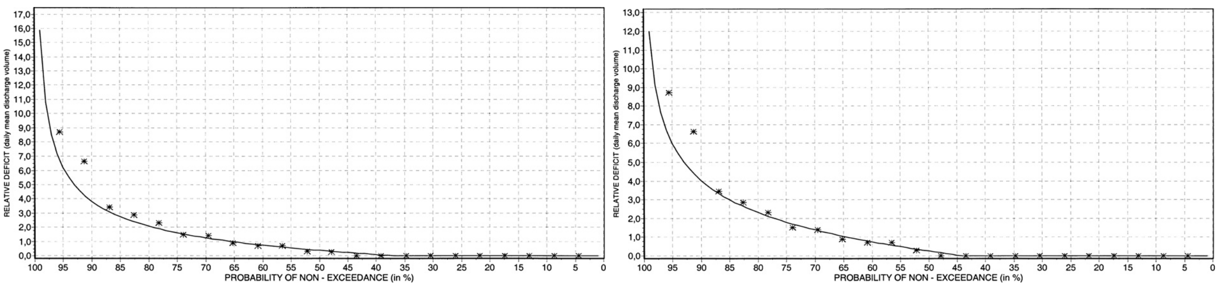


Figure 4.21 Fitted GP distribution functions for Bagamati River with different values for α and d_{min}. Left: $\alpha = 0.005$, $d_{min} = 1$ day ($\alpha = 0.005$, $d_{min} = 3$ days is identical; $\alpha = 0.010$, $d_{min} = 1$ day is identical; and $\alpha = 0.010$, $d_{min} = 3$ days is identical). Right: $\alpha = 0.005$, $d_{min} = 5$ days ($\alpha = 0.010$, $d_{min} = 5$ days is identical).

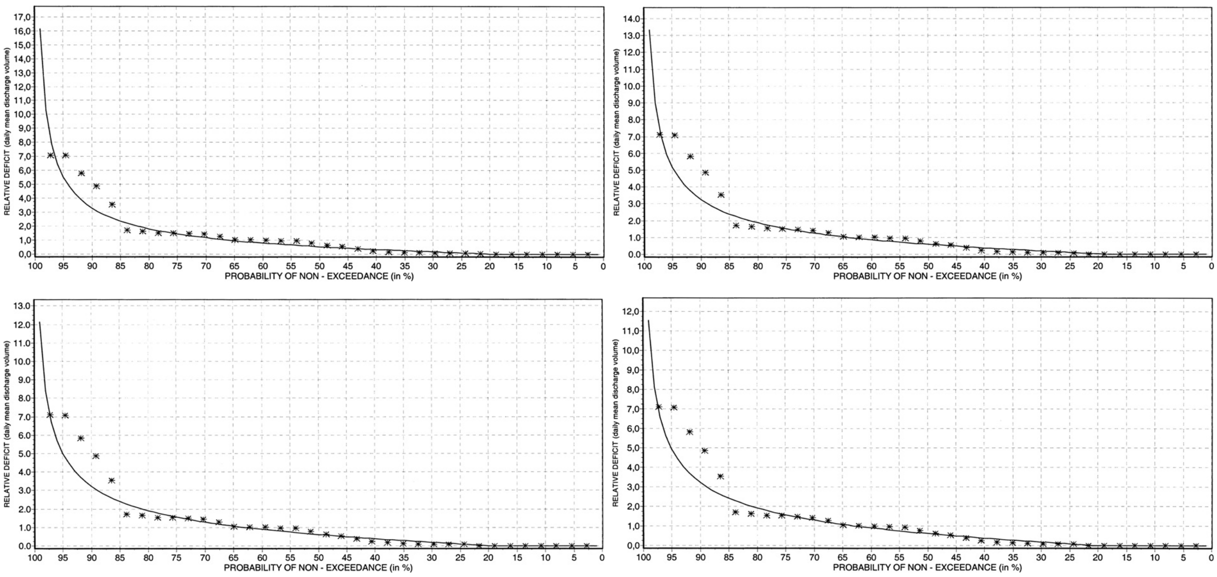
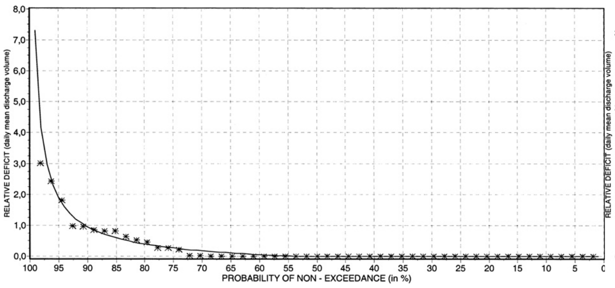
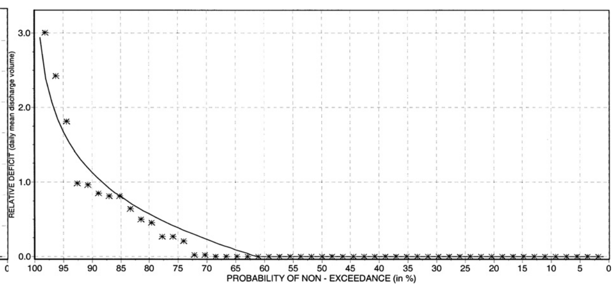


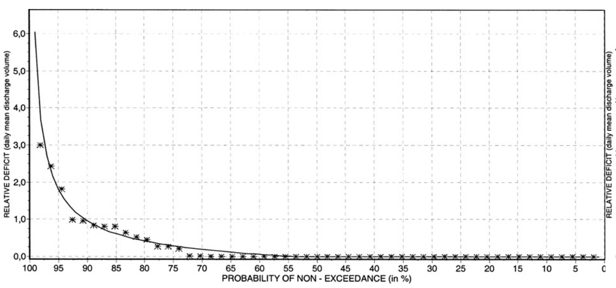
Figure 4.22 Fitted GP distribution functions for Ngaruroro with different values for α and d_{min}. Upper left: $\alpha = 0.005$, $d_{min} = 1$ day ($\alpha = 0.005$, $d_{min} = 3$ days is identical). Upper right: $\alpha = 0.005$, $d_{min} = 5$ days. Lower left: $\alpha = 0.010$, $d_{min} = 3$ days. Lower right: $\alpha = 0.010$, $d_{min} = 5$ days.



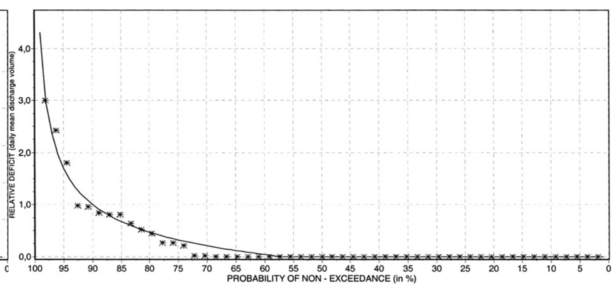
$\alpha = 0.000$ and $d_{min} = 3$ days



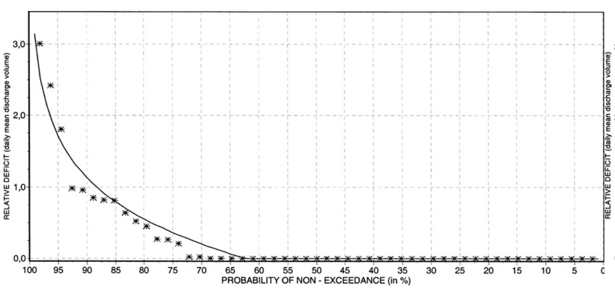
$\alpha = 0.000$ and $d_{min} = 5$ days



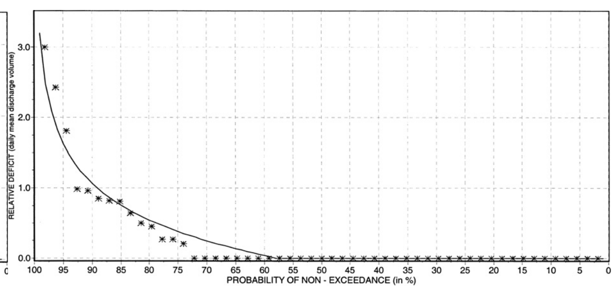
$\alpha = 0.005$ and $d_{min} = 1$ days



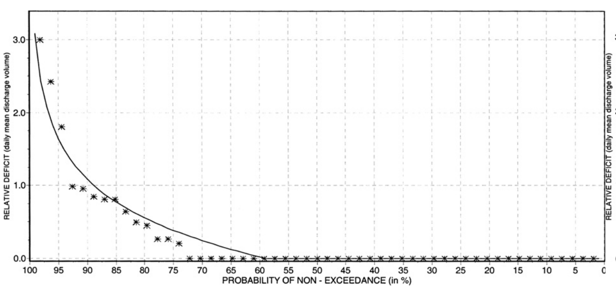
$\alpha = 0.005$ and $d_{min} = 3$ days



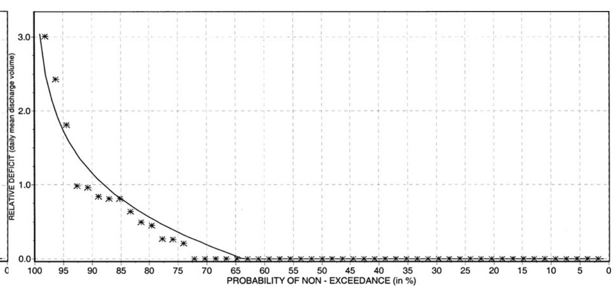
$\alpha = 0.005$ and $d_{min} = 5$ days



$\alpha = 0.010$ and $d_{min} = 1$ days



$\alpha = 0.010$ and $d_{min} = 3$ days



$\alpha = 0.010$ and $d_{min} = 5$ days

Figure 4.23 Fitted GP distribution functions for Honokohau Stream with different values for α and d_{min}.

When Tallaksen et al. (1997) applied the MA(n-day)-filter to pool mutually dependent droughts they found that no further removal of minor droughts was necessary to conduct a frequency analysis. However, in NIZOWKA2003 no estimation was possible for Honokohau Stream when the parameters were set to $\alpha = 0.000$ and $d_{min} = 1$ day. Therefore for this case also several combinations of α and d_{min} were tested for the MA(15-day)-filter. It still could be seen that the best fit to the most extreme drought events was achieved by a combination of low parameter values, i.e. $\alpha = 0.000$ and $d_{min} = 3$ days or $\alpha = 0.005$ and $d_{min} = 1$ day, and that combinations of higher parameter values resulted in underestimates of the extreme events (Figure 4.23) The first combination, $\alpha = 0.000$ and $d_{min} = 3$ days is advisable, since it resulted in the highest estimate of the 50-year event, without it being an unreasonably high estimate.

4.4.2 Application of a frequency analysis with NIZOWKA2003

The frequency analysis was conducted on PDS derived with the IT-method with the following parameters: $t_c = 5$ days, $\alpha = 0.005$ and $d_{min} = 3$ days for all streams except for Honokohau Stream, where a MA(15-day)-filter was applied with $\alpha = 0.000$ and $d_{min} = 3$ days. With NIZOWKA2003 distribution functions that fitted well to the whole range of the observed drought events could be found for the deficit volumes and durations of drought events of perennial streams, frost effected perennial streams as well as for drought durations of most intermittent streams. Graphs with the observed events and fitted distribution functions are presented in Appendix 3. For intermittent streams a drawback of NIZOWKA2003 is that zero-flow periods can not be treated as censored data and distributions of deficit volumes can not be estimated, also the possibilities of separating events belonging to different populations are limited. A data record of only four years from the only ephemeral stream in the global data set, Dawib was too short to conduct a frequency analysis. For streams with catchments which are only partly influenced by frost it was in addition looked at the differences when performing a frequency analysis based on seasonal data as compared to all-year data.

Number of zero-drought years

The distribution of drought events could be modelled well even when the PDS did not contain any drought event for more than 40 % of the years on record (at a threshold level of *Q*90: Lindenborg showed 45.9 %, Rhine (all-year) 41.3 % and Bagamati River 45.5 %). The highest percentage of zero-drought years (75 %) was observed for the river Lambourn at a threshold of *Q*90. For drought duration no fitted distribution function was accepted at a significance level of 0.05 and for the deficit volumes none of the fitted functions described the extreme events well. A high number of zero-drought years disturbed the estimation only when at the same time the number of observed drought events was small.

Threshold level

For most perennial streams well-fitting distribution functions could be estimated for PDS derived with both threshold levels, *Q*90 and *Q*70. No conclusion could be drawn that distribution functions could be fitted better to the PDS of either one of the threshold levels, since this varied from stream to stream even though the streams might have the same regime and hydrograph characteristics. In several cases also the threshold level giving the better fit varied between deficit volume and duration for one stream.

For intermittent streams usually the choice of an appropriate threshold level is restricted, due to the high percentages of zero-flow and the fact that the PDS should not include any multi-year droughts.

Multi-year droughts

The method suggested by Zelenhasić & Salvai (1987) is only valid for within-year droughts and usually it is advisable to conduct a frequency analysis for multi-year droughts on annual data rather than daily (Tallaksen et al. 2004). Here multi-year droughts were observed for the following streams: Sabar at Alfartanejo with $Q_0 = MQ$, two events, Lambourn at Shaw with $Q_0 = Q70$, four events, Lambourn at Shaw with $Q_0 = Q90$, one event and Ray at Grendon Underwood with $Q_0 = Q50$, one event. The chosen distribution functions either did not fit well in the extreme range or to the complete sample (Lambourn, Ray) or the drought sample did not include a large range of different drought durations (Sabar) so that it can not be decided whether a fitted distribution functions also represents the extreme range well. And since the method is not valid for multi-year droughts, the results should not be trusted and annual data should be used instead.

4.4.2.1 Streams with catchments partly influenced by frost

The catchments of the rivers Rhine and Hurunui experience a frost season only in some parts and for both streams the percentiles $Q90$ and $Q70$ are slightly higher for all-year data than for only summer data (Section 3.2.2.2). The estimates of the summer 50-year events and of the all-year 50-year events deviated only slightly, when the same threshold level was applied. This was true for estimates of the deficit volume as well as duration for the threshold levels $Q90_S$ ($Q90$ of the summer FDC), $Q90_Y$ ($Q90$ of the all-year FDC), $Q70_S$ and $Q70_Y$. Usually, the estimates of the summer 50-year events were slightly higher than those of the all-year 50-year events, except for the deficit volumes with the threshold levels $Q90_Y$ and $Q90_S$. Whether distribution models could be fitted satisfyingly well depended more on the chosen threshold level rather than on the chosen data period.

In the cases of the rivers Hurunui and Rhine it does not really matter whether the calculations are conducted only on summer data or on all-year data, as long as the same discharge value is applied as threshold level. If a specific percentile from the FDC is to be applied as threshold level it is advisable to use the higher value from the all-year FDC, since this results in the more severe drought events.

Calculations of summer drought events for Pecos River revealed a major problem in the identifications procedure of summer droughts as implemented in NIZOWKA2003, for this type of hydrological regime. In NIZOWKA2003 drought events which start during the summer but continue into the winter season are considered as summer droughts when the major part of the event lies within the summer season, i.e. more than half of the days belong to the summer season. The Pecos River has a very short winter season, which at the same time is the dry season in the meteorological regime. This means that no clear snow melt peak is visible in the hydrograph of the stream. When identifying drought events with the IT-method it now happened that one event started during one summer, lasted the whole winter and continued for several weeks during the next summer. This way more than half of the drought event belonged to the summer season, but it still included a whole winter season. For streams experiencing only a short winter season, as it does Pecos River a different method of identifying summer drought events has to be applied. Different possibilities have already been discussed in Section 3.2.2.2.

It can be seen that for streams whose catchment areas are only partly influenced by frost no general recommendation can be given, since the best method strongly depends on the proportion of precipitation that is hold back during the winter and on the possibilities one has to identify summer drought events.

4.4.3 Generalized Pareto and Poisson

4.4.3.1 Use of the Generalized Pareto distribution model

According to Tallaksen et al. (2004) the Generalized Pareto distribution (GP) appears as the limit distribution of scaled excess over an upper limit, u. As stated earlier a PDS of drought events after the exclusion of minor events can be seen as such, but different authors have also successfully been fitting other distribution models to model a PDS of drought events. Here it is thought to find out whether the use of the GP-model can be advisable in general or not. Different distribution models have been fitted to PDS of deficit volumes and durations for all perennial streams in the global data set for threshold levels of $Q90$ and $Q70$ and to PDS of durations with higher threshold levels for the intermittent streams. It then was compared how well the distribution models fitted to the whole data sample by a χ^2-goodness-of-fit test, and how well they fitted in the extreme end of the severest drought events by visual inspection. In addition their estimates of the 50-year event were compared. The results for the GP-model as well as for the model with the highest attained significance level, ρ can be seen in Table 4.16 - Table 4.19. Distribution models were only considered when they could be accepted to fit the sample at least on a significance level of 0.05. The following conclusions could be drawn.

Table 4.16 Comparison of the GP-model to other models for the estimation of deficit volumes with $Q_0 = Q90$ in terms of the attained significance level and the estimates for the 50-year-event

Station	**Deficit Volume of the 50-year-event (relative to daily mean discharge volume)**		**Distribution model with highest ρ**	**χ^2-test: attained significance level ρ**	
	Poisson, GP	**Models with highest ρ**		**GP**	**Model with highest ρ**
Honokohau MA(15-day) d_{min}=3 d, α=0.00	41.6	25.69	Pascal, Pearson	0.19456	0.27477
Dawib			No estimation		
Pecos (summer)	4.70	3.76	Poisson, Db. Exp.	1.00000	1.00000
Elands River Drift d_{min}=5 d	2.95		Poisson, Gen. Pareto	0.91187	
Sundurijal	10.80		Poisson, Gen. Pareto	0.23777	
Alfartanejo			No estimation		
Soledad			No estimation		
Grendon Underwood			No estimation		
Shaw	41.40	32.18	Poisson, Log Normal	0.73470	0.76247
Lindenborg Bro	22.22	14.42	Pascal, Log Normal	0.49865	0.74300
Kuripapango	10.30	10.29	Pascal, Gen. Pareto	0.12531	
Mandamus (summer)	12.85		Poisson, Gen. Pareto	0.26460	
Rosten (summer)	5.60		Poisson, Gen. Pareto	0.50582	
Kudymkar (summer)	*5.94*	5.06	Pascal, Log Normal	0.03358	0.07801
Lobith $Q90_Y$ (year)	17.48	16.28	Pascal, Log Normal	0.24270	0.43748
Lobith $Q90_S$ (summer)	*17.29*		Poisson, Gen. Pareto	0.03166	
Liavatn (summer)	9.47	10.48	Poisson, Log Normal	0.06636	0.09417

Table 4.17Comparison of the GP-model to other models for the estimation of durations with Q_0 = $Q90$ in terms of the attained significance level and the estimates for the 50-year-event

Station	**Duration of the event with *T*=50 a (days)**		**Distribution model with highest ρ**	**χ^2-test: attained significance level ρ**	
	Poisson, Gen. Pareto	**Model with highest ρ**		**Gen. Pareto**	**Model with highest *ρ***
Honokohau *MA*(15-day) d_{min}=3 d, α=0.00	61.2	46.2	Pascal, Db. Exp.	0.08537	0.16543
Dawib			No estimation		
Pecos $Q90_S$ (summer)			Pascal, Db. Exp.	0.00975	0.00760
Elands River Drift d_{min}=5 d	124.1	101.1	Poisson, Db. Exp.	0.24683	0.31562
Sundurijal	175.9		Poisson, Gen. Pareto	0.25073	
Alfartanejo			No estimation		
Soledad			No estimation		
Grendon Underwood			No estimation		
Shaw		*325.4*	Poisson, Log Normal	0.00537	0.02133
Lindenborg Bro	193.6	231.8	Pascal, Log Normal	0.39342	0.40911
Kuripapango	81.2	114.5	Pascal, Log Normal	0.64819	0.65015
Mandamus $Q90_S$ (summer)			Poisson, Db. Exp.	0.00046	0.00768
Rosten (summer)	48.9	56.4	Poisson, Log Normal	0.14750	0.55455
Kudymkar (summer)	99.9	145.9	Pascal, Log Normal	0.13416	0.71329
Lobith $Q90_Y$ (year)	*129.8*	139.4	Pascal, Log Normal	0.04056	0.66257
Lobith $Q90_S$ (summer)	*127.2*	128.4	Poisson, Log Normal	0.02466	0.32022
Liavatn (summer)	35.8	42.2	Poisson, Log Normal	0.17667	0.41154

Table 4.18 Comparison of the GP-model to other models for the estimation of deficit volumes with Q_0 = *Q*70 (for the intermittent streams the applied Q_0 is stated with the stream) in terms of the attained significance level and the estimates for the 50-year-event

Station	**Deficit Volume of the event with *T*=50 a (relative to daily mean discharge volume)**		**Distribution model with highest ρ**	**χ^2-test: attained significance level ρ**	
	Poisson, Gen. Pareto	**Model with highest *ρ***		**Gen. Pareto**	**Model with highest *ρ***
Honokohau *MA*(15-day) d_{min}=3 d, α=0.00	145.67	140.62	Pascal, Log Normal	0.11791	0.18501
Dawib			No estimation		
Pecos, $Q70_S$ (summer)	21.28	16.65	Poisson, Log Normal	0.15995	0.21482
Elands River Drift d_{min}=5 d	24.62		Poisson, Gen Pareto	0.67479	
Sundurijal	38.35	28.72	Poisson, Johnson	0.12662	0.28711
Alfartanejo, *MQ* d_{min}=200 d		346.1	Poisson, Johnson	0.00000	0.79881
Soledad alpha = 0.6			No estimation possible		
Grendon Underwood *MQ*, d_{min}=200			No estimation possible		
Shaw	180.12		Poisson, Gen. Pareto	0.27928	
Lindenborg Bro	*111.94*	54.65	Poisson, Log Normal	0.02340	0.06676
Kuripapango	81.27	36.58	Poisson, Weibull	0.39549	0.42570
Mandamus $Q70_S$ (summer)	*44.27*		Poisson, Gen. Pareto	0.04139	
Rosten (summer)	*38.21*	25.41	Poisson, Weibull	0.03310	0.77118
Kudymkar (summer)	34.54	28.7	Poisson, Log Normal	0.14357	0.54424
Lobith $Q70_Y$ (year)	72.62		Poisson, Gen. Pareto	0.39804	
Lobith $Q70_S$ (summer)	77.05		Poisson, Gen. Pareto	0.66395	
Liavatn (summer)	49.63		Poisson, Gen. Pareto	0.43548	

Table 4.19 Comparison of the GP-model to other models for the estimation of deficit volumes with $Q_0 = Q70$ in terms of the attained significance level and the estimates for the 50-year-event

Station	**Duration of the event with *T*=50 a (days)**		**Distribution model with highest ρ**	**χ^2-test: attained significance level ρ**	
	Poisson, Gen. Pareto	**Model with highest ρ**		**Gen. Pareto**	**Model with highest ρ**
Honokohau *MA*(15-day) d_{min}=3 d, α=0.00	91.3	89.1	Pascal, Weibull	0.05880	0.48157
Dawib			No estimation		
Pecos $Q70_S$ (summer)	*151.0*	135.6	Poisson, Log Normal	0.00480	0.78661
Elands River Drift d_{min}=5 d	387.4	504.9	Poisson, Log Normal	0.17159	0.22187
Sundurijal	416	202.3	Poisson, Johnson	0.08398	0.82779
Alfartanejo MQ d_{min}=200 d	494.6	525.2	Poisson, Log Normal	0.06100	0.48610
Soledad alpha = 0.6			No estimation possible		
Grendon Underwood *Q50*	706.2	458.3	Poisson, Weibull	0.08166	0.25368
Shaw	553.2	556.7	Poisson, Log Normal	0.08105	0.31311
Lindenborg Bro	*278.1*	372.9	Poisson, Log Normal	0.02643	0.18899
Kuripapango	204.4	262.9	Poisson, Log Normal	0.24127	0.50468
Mandamus $Q70_S$ (summer)	*133.5*	*147.1*	Poisson, Log Normal	0.00847	0.01907
Rosten (summer)	89.6		Poisson, Gen. Pareto	0.75593	
Kudymkar (summer)	162.6	165.3	Poisson, Pearson	0.33670	0.96526
Lobith $Q70_Y$ (year)	225.0	228.7	Poisson, Log Normal	0.20599	0.24028
Lobith $Q70_S$ (summer)	228.0		Poisson, Gen. Pareto	0.27521	
Liavatn (summer)	61.5		Poisson, Gen. Pareto	0.26455	

When several distribution models gave a good fitting function the estimates of the 50-year event by the GP-model were slightly higher for the deficit volume than estimates by other models, whereas they were slightly lower for duration. But in general estimates of different well-fitting models were most often very similar for both, the deficit volume as well as duration. In these cases the chosen function of the GP-model fitted better or equally well in the extreme end of the sample than any other distribution function. In cases where the estimates were not so similar, the GP-model fitted better in the extreme range than any other distribution function as for example in the case of Lindenborg (Figure 4.24).

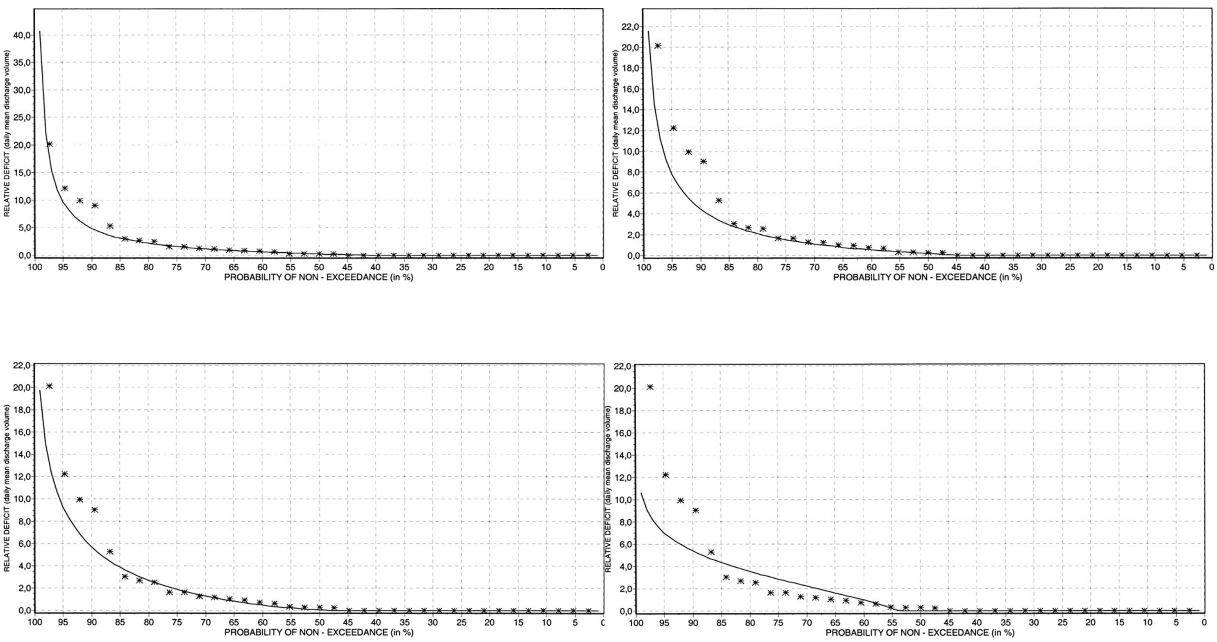


Figure 4.24 Different distribution models fitted to a PDS of deficit volumes for Lindenborg. Upper left: Generalized Pareto. Upper right: Log-normal. Lower left: Weibull. Lower right: Double Exponential.

In a few cases the GP-model could not be accepted to accurately describe the sample on a significance level of 0.05, but no special type of regime could be identified where this happened more often than for others. It was observed for perennial as well as intermittent streams, seasonal and non-seasonal streams, and streams of long record length and short record length. It happened slightly more often for a threshold level of $Q70$ than $Q90$.

In general it can be concluded that for all types of regimes the GP-model is a good choice for PDS, when one wants to conduct a frequency analysis for drought durations and also for deficit volumes of perennial streams. For deficit volumes of intermittent streams the applicability of the GP-model could not be tested with NIZOWKA2003.

4.4.3.2 Use of the Poisson distribution model

For the estimation of $\Pr(Z_t = k)$ a Poisson or a Pascal distribution model could be chosen. When the GP-model was used for the estimation of $H_t(x)$, it was found that the differences in the estimates of the 50-year event by using either the Poisson or the Pascal distribution model was less than 0.5 % for all streams, no matter how well either one of those were fitted to the sample. This corresponds to what is stated in Stedinger et al. (1993), namely that "for large-return-period events, the actual probabilistic model for arrivals is not important, provided different models yield the same average number of arrivals per year."

4.4.4 Global comparison

The question whether the method presented by Zelenhasić & Salvai can be applied to streams with different types of regimes can clearly be answered with 'yes', provided that the prerequisites of a proper frequency analysis are assured, i.e. the events are iid, the data record of the discharge series is long enough and the PDS of drought events contains an appropriate minimum number of events as well as that the PDS does not contain any multi-year events. The applicability of a frequency analysis conducted by NIZOWKA2003 as well as the use of the GP-model for $H_t(x)$ and the Poisson-model for $\Pr(Z_t = k)$ are summarised in Table 4.20.

Table 4.20 Applicability of a frequency analysis conducted with NIZOWKA2003 as well as the use of the GP-model for $H_t(x)$ and Poisson-model for $\Pr(Z_t = k)$ for streams with different streamflow types

Streamflow type	**Evaluation**
Perennial	NIZOWKA2003 is a good tool to conduct a frequency analysis for drought duration and deficit volume as long as no multi-year droughts are present. The use of GP-model for $H_t(x)$ and the Poisson-model for $\Pr(Z_t = k)$ can be recommended.
Perennial, seasonal	The way of selecting summer drought events should be modified, since severe summer drought events which turn into long winter droughts stay unconsidered and are treated as a year without any summer drought. Drought durations and deficit volumes can be analysed. The use of GP-model for $H_t(x)$ and the Poisson-model for $\Pr(Z_t = k)$ can be recommended
Intermittent	For a drought study of the *wet season* NIZOWKA2003 is a good tool to conduct a frequency analysis for drought duration and deficit volume as long as no zero-flow periods occur during the wet season. During the *dry season* and when zero-flow periods occur, deficit volumes can not be analysed. No analysis is possible when multi-year droughts occur. The use of GP-model for $H_t(x)$ and the Poisson-model for $\Pr(Z_t = k)$ can be recommended.
Ephemeral	The method was not tested.

Since the use of GP-model for $H_t(x)$ and the Poisson-model for $\Pr(Z_t = k)$ can be recommended for streams of all streamflow types, it can also be recommended for global comparisons.

A general disadvantage of NIZOWKA2003 is that unfinished events are excluded, without reducing the whole series accordingly. To reduce this problem the discharge series should start and end within the high flow season. Then NIZOWKA2003 is a good tool which allows to compare drought durations of perennial and intermittent streams. For frost influenced streams the use is limited, when severe summer droughts occur that turn into long winter droughts. For a global comparison of deficit volumes it can only be used for seasons without zero-flow periods, since these can not be treated as censored data.

5 Conclusions

Droughts can be characterised through different drought characteristics. Two main concepts can be distinguished, those of low flow characteristics and deficit characteristics. In this study more focus was on the deficit characteristics. The evaluated low flow indicess were the percentiles from the FDC as well as the MAM(*n*-day). Deficit characteristics were derived with the threshold level method and different pooling-procedures were tested, the IT-method, the MA(*n*-day)-filter and the SPA. For deficit characteristics derived with the threshold level method and pooled with the IT-method a frequency analysis was conducted and the programme NIZOWKA2003 was tested. These methods to derive drought characteristics were evaluated according to their:

a) applicability for drought studies of perennial, intermittent and ephemeral streams;
b) general applicability for the comparison of different types of regimes;
c) data requirements and limitations.

Thereby the data requirements and limitations either can depend on the particular method or on data properties of a stream type. It could be seen that the most critical data properties are winter low flows caused by frost as well as zero-flow periods. Another important aspect is the choice of the year shift.

The evaluation of the low flow indices showed that the FDC is a good graphical method to compare the variability of different streams. The great advantage of the percentiles from the FDC is that they give valuable information for all streamflow types, revealing also the percentage of zero-drought values for intermittent and ephemeral streams. As such FDCs based on all-year data can be used for a global comparison of streams with different streamflow types. FDCs can also be calculated for specified seasons, which is especially necessary for streams with winter-low flow caused by frost. Then the comparison is more complicated, since the FDC is very sensitive to the chosen dates of the season. It was shown that FDCs for summer seasons differing by two weeks vary considerably, and the summer FDC of one stream can not be directly compared to all-year FDCs of other streams. A further advantage of the FDC is that it can be calculated for data records of any length.

The MAM(*n*-day) is a good low flow index for perennial streams, which also includes to some extent the aspect of duration of low flow periods in contrast to the percentiles from the FDC. The aspect of duration is included in the averaging period, *n*, and useful information can in particular be obtained, when MAM(n-day)-values are calculated for several averaging periods, for example n equal to 1, 10 and 30. Since the MAM(n-day) is less sensitive to the chosen dates of the summer season, perennial streams with and without frost influence can be compared. For intermittent and ephemeral streams the MAM(n-day) is limited, since they are often equal to zero, except when a very large averaging interval is chosen or when they are calculated only for the wet season. As such they can not be recommended in general for a global comparison, but they can be recommended for the comparison of perennial streams with frost influence to others without frost influence. For the calculation of the MAM(n-day) one has to keep in mind the importance of the chosen date for the year shift. If the year shift lies within the low flow season, the discharge values of some days might be considered in the AM(n-day)-values of two succeeding years. The year shift should therefore be for perennial streams in the high flow season, for frost influenced perennial streams in the winter season and for intermittent streams in the season that is of least interest in a specific case.

The threshold level method and connected pooling-procedures are not relevant for ephemeral streams, since in this case the most informative deficit characteristics from daily discharge series are the duration of zero-flow periods, as well as the interevent excess volume of any flow event. In general, also the use of annual discharge series is recommended for ephemeral streams. For intermittent and perennial streams the threshold level method based on daily data is suitable and provides detailed information. However, one has to keep in mind that the deficit volumes of intermittent and perennial streams are not directly comparable, due to the zero-flow periods of intermittent streams.

As pooling-procedure in connection with the threshold level method the IT-method can be applied with t_c = 5 days for perennial streams with and without frost influence as well as for intermittent streams. It is not recommended for fast responding streams with a flashy hydrograph. For these streams periods below as well as above the threshold level are often very short but might vary considerably in their deficit volumes and excess volumes respectively. Therefore, a pooling-procedure, which considers also the volumes, should be applied. Since the IT-method considers only the interevent time as pooling criterion but not the ratio of interevent excess volume and deficit volume, the pooling is comparable for perennial and intermittent streams.

The SPA can be applied as pooling-procedure to all perennial and intermittent streams, without having to define any parameters. It is however only advisable for the selection of an

AMS of drought events, but not necessarily for a PDS, since droughts occurring after a major drought can be pooled to the major drought without extending the drought duration or being recorded as separate events. The period after a major drought is rather considered to be drought-free. Further disadvantages of the SPA are that only low threshold levels can be used and that the SPA returns a high number of minor droughts. Pooling can not be compared for perennial and intermittent streams, due to zero-flow periods, since the SPA bases pooling on deficit and excess volumes. The application of the SPA can thus not be recommended for global comparisons.

As pooling-procedure in connection with the threshold level method the MA(n-day)-filter seems to be the most flexible approach, since it can be used for perennial and intermittent streams with different catchment geology as well as different climates. Its parameter, n can easily be optimised, and values between 10 and 15 days can be recommended for n. The procedure should be tested in more detail also for intermittent streams, especially for streams, which also experience frequently zero-flow periods during the wet season or flow events during the dry season. The disadvantage of the MA(n-day)-filter is that it modifies the discharge series and hence duration and deficit volume are modified. The MA(n-day)-filter is probably also applicable for global comparisons. Zero-flow periods should not harm the comparability of pooling, since only zero-flow values close to periods with flow are set in relation to values larger than the threshold level.

In general, a frequency analysis in the way presented by Zelenhasić & Salvai (1987), who suggested to derive the cumulative distribution function of the largest streamflow drought occurring in a given time interval from a PDS of drought events, can be conducted for streams of all streamflow types as long as no multi-year droughts are present. The use of a Generalized Pareto model for $H_t(x)$ (the distribution function of all drought events expressed as deficit volume or duration within the time interval [0, t]) as well as a Poisson model for $\Pr(Z_t = k)$ (the probability that k events occur during the time interval [0, t]) can be recommended, since they are the theoretically most correct distribution models and it was found, that they did not perform worse than other distribution models. Of course the general prerequisites of a frequency analysis have to be assured.

To conduct a frequency analysis as presented by Zelenhasić & Salvai (1987) NIZOWKA2003 is a good tool, in particular for perennial streams. For intermittent streams a drawback is that zero-flow periods can not be treated as censored data and thus no proper frequency analysis of deficit volumes can be conducted. For a frequency analysis of summer droughts for frost influenced streams, the way of selecting summer droughts has to be modified, since severe summer droughts can stay unconsidered when they turn into a long winter drought.

Since in frost influenced streams a second type of droughts, so called winter droughts, occur, it is often favourable to base a drought study only on the summer season. Therefore the seasons have to be specified. For the derivation of deficit characteristics it has to be decided whether the threshold level should be based on all-year or on seasonal data, and the type of each drought has to be identified. For frost influenced streams the specification of the summer season was here done by choosing fixed dates based on a combination of mean monthly temperature data as well as the occurrence of the spring flood. The error of this method is still to be evaluated and its importance depends also on the applied analysis tools. For example the FDC is very sensitive to the chosen dates of the season, while they have less influence on the MAM(n-day). Special problems arise for streams with frost influence only in some parts of the catchment, since droughts during a relatively long period of the year could either be summer droughts as well as winter droughts. Also for streams with a short winter season and a winter dry climate the specification of the summer season is complicated, due to the missing spring flood.

For seasonal calculations of deficit characteristics it is in general possible to derive the drought series only from the discharge data of the chosen season. A frequency analysis, however, is much more complicated when unfinished events are included and therefore the termination of summer droughts at the last day of the summer season is problematic. It is recommended to proceed in the following way:

1. specification of the summer season;
2. derivation of a series of deficit periods with discharge below the threshold level for the whole year;
3. identification of the season of each of these deficit periods, for example according to which season the longer part of the deficit period belongs to;
4. pooling of the summer periods with discharge below the threshold level.

In this way the end of the summer is allowed to vary from year to year and no mixing of events is additionally caused by pooling. The remaining problem is how to treat severe summer droughts that turn into a long winter drought. Should they be terminated at the end of the summer season, which leaves one with cut off events, should they be continued throughout the whole winter, which results in droughts of mixed origin or should the deficit volume be terminated at the end of the summer while the duration is continued? This is the main topic for a further study.

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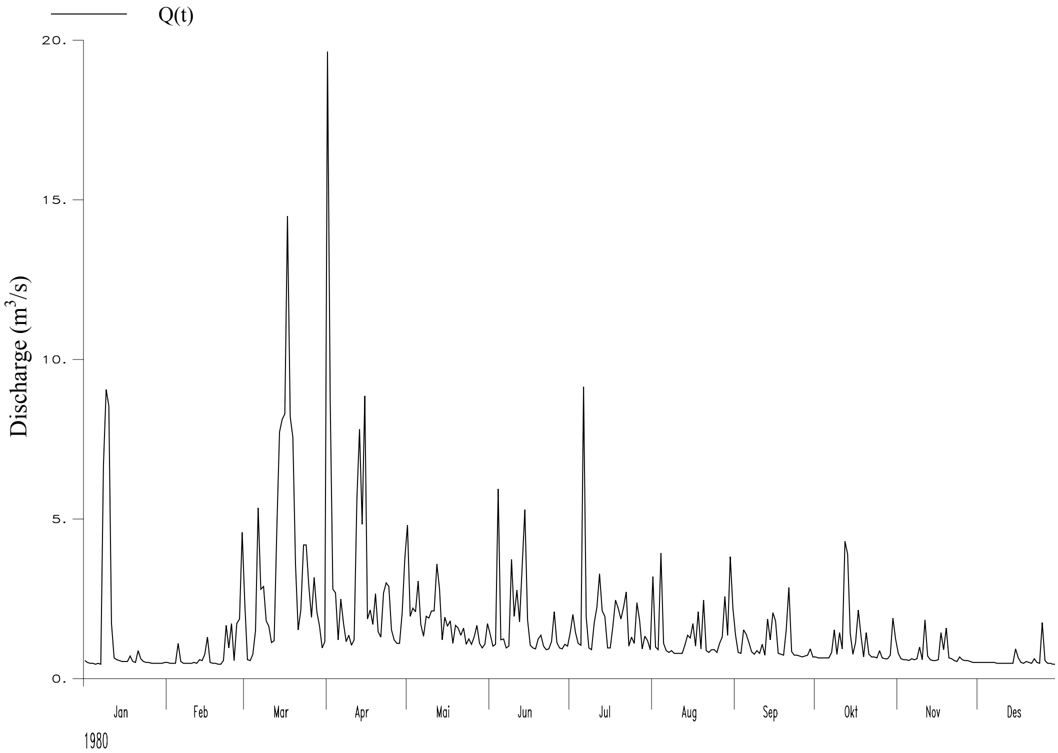
Appendix 1
Daily discharge curves



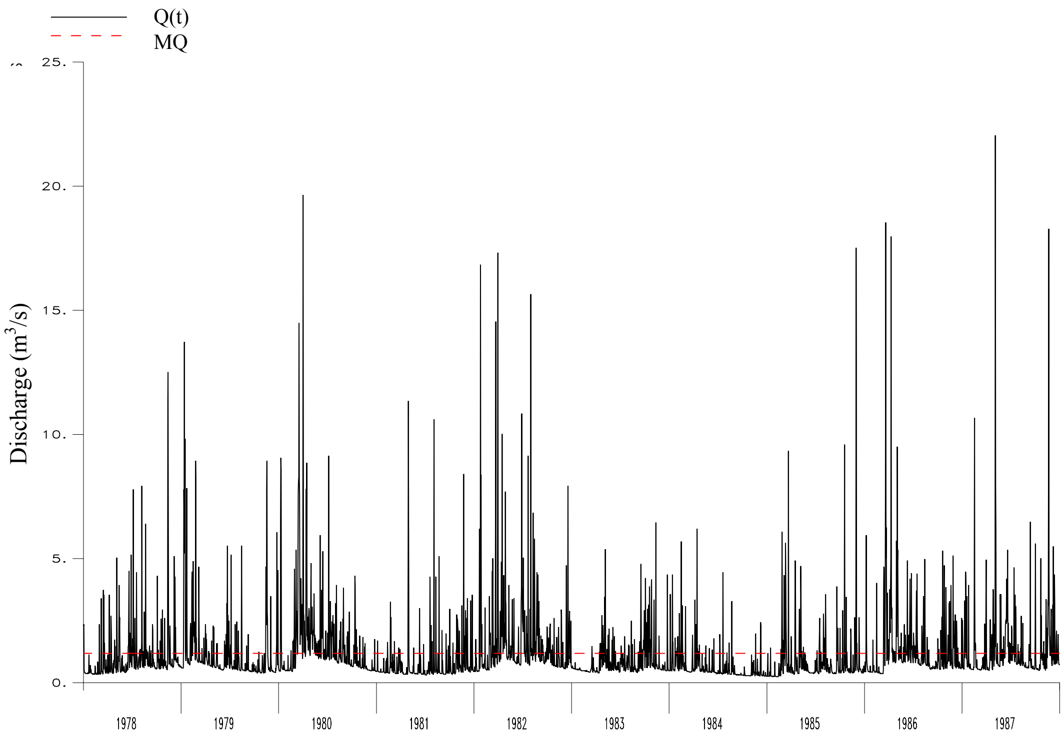


Figure A1.1 Hydrographs of Honokohau Stream at Honokohau, Hawaii. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1978-1987.

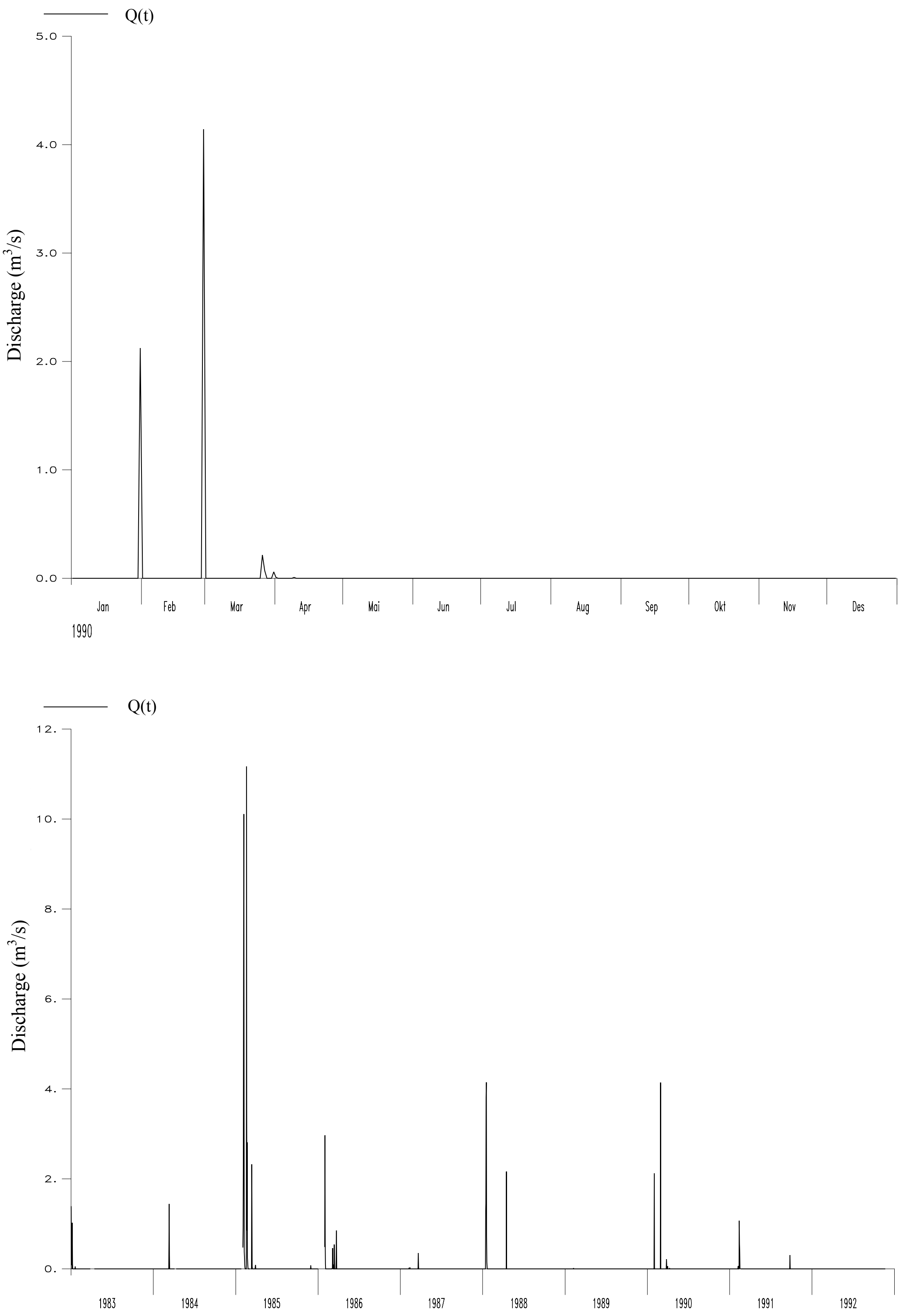
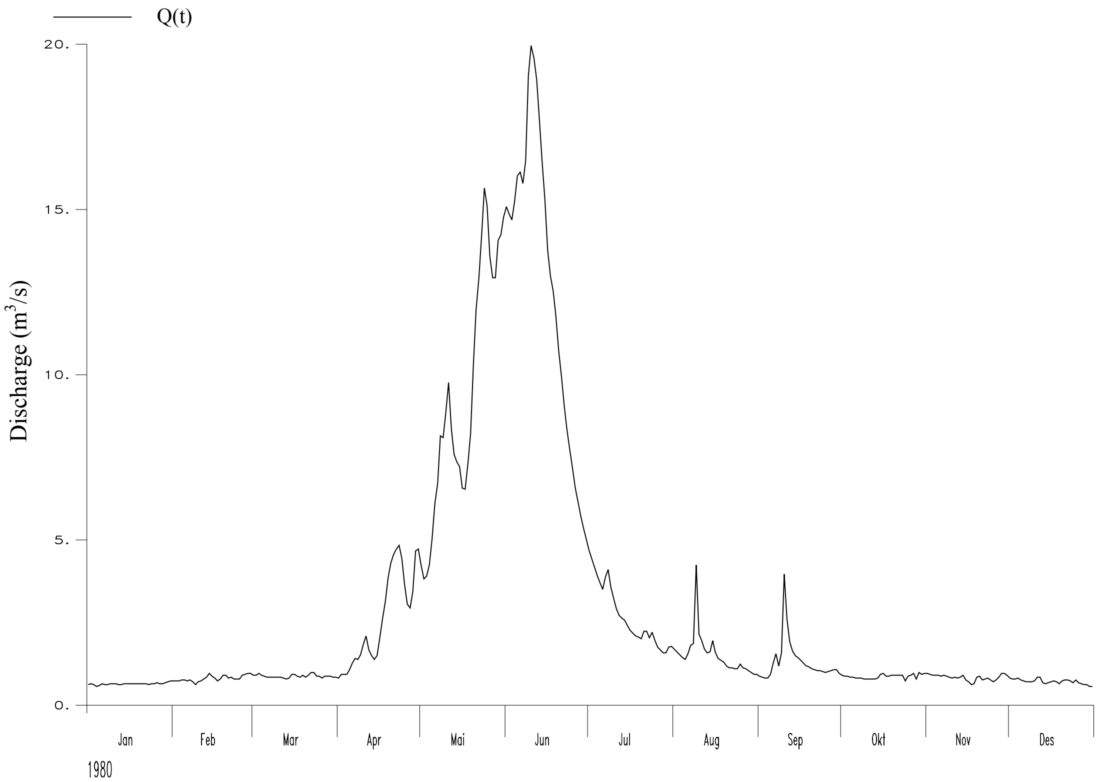


Figure A1.2 Hydrographs of Dawib at Dawib, Namibia. Upper: Daily discharge data from 1990. Lower: Daily discharge data from 1983-1992.



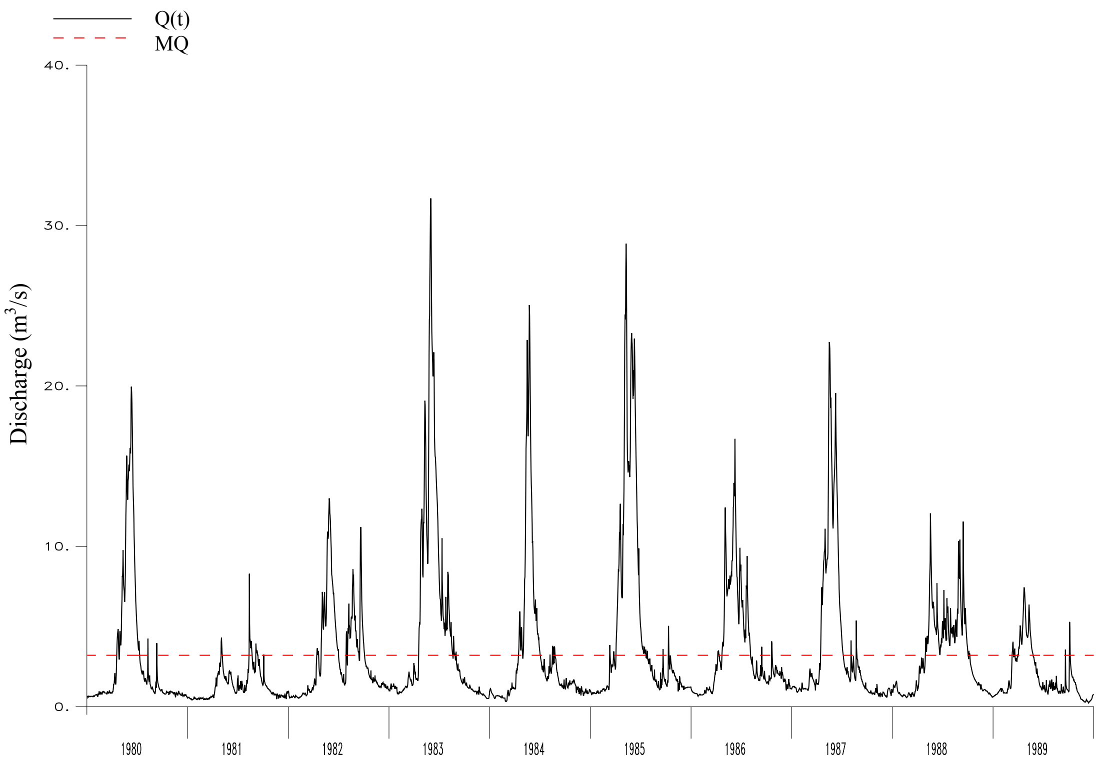
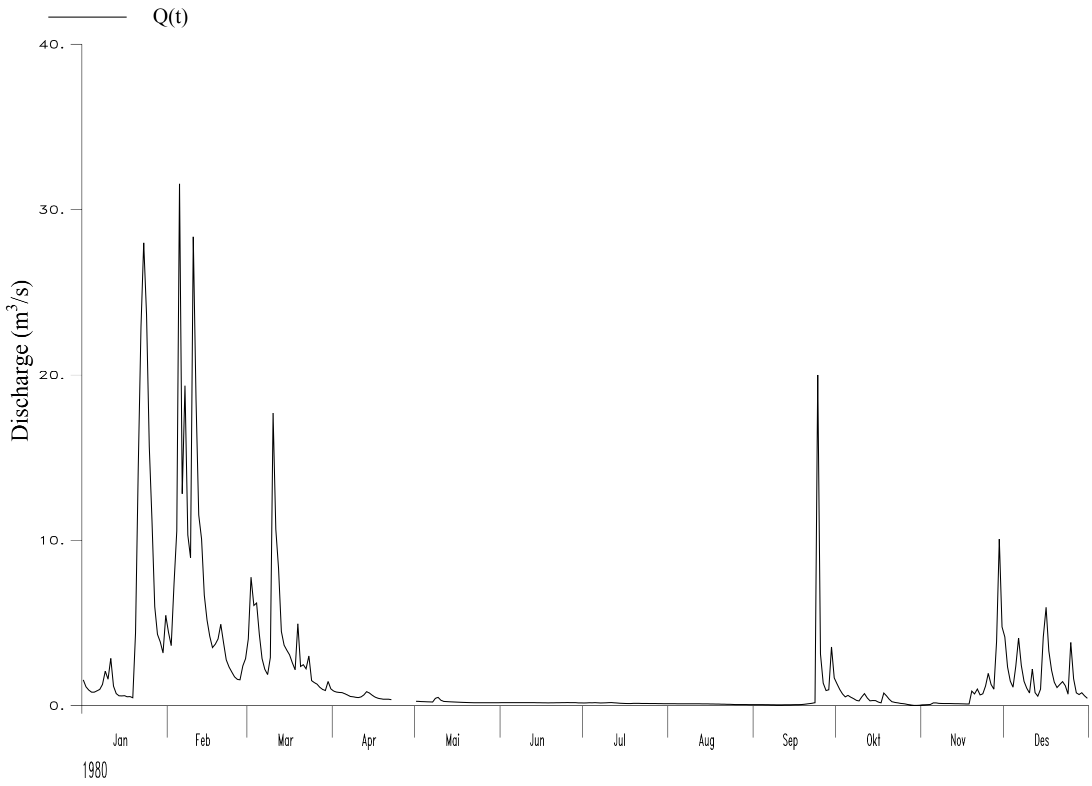


Figure A1.3 Hydrographs of Pecos River at Pecos, USA. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



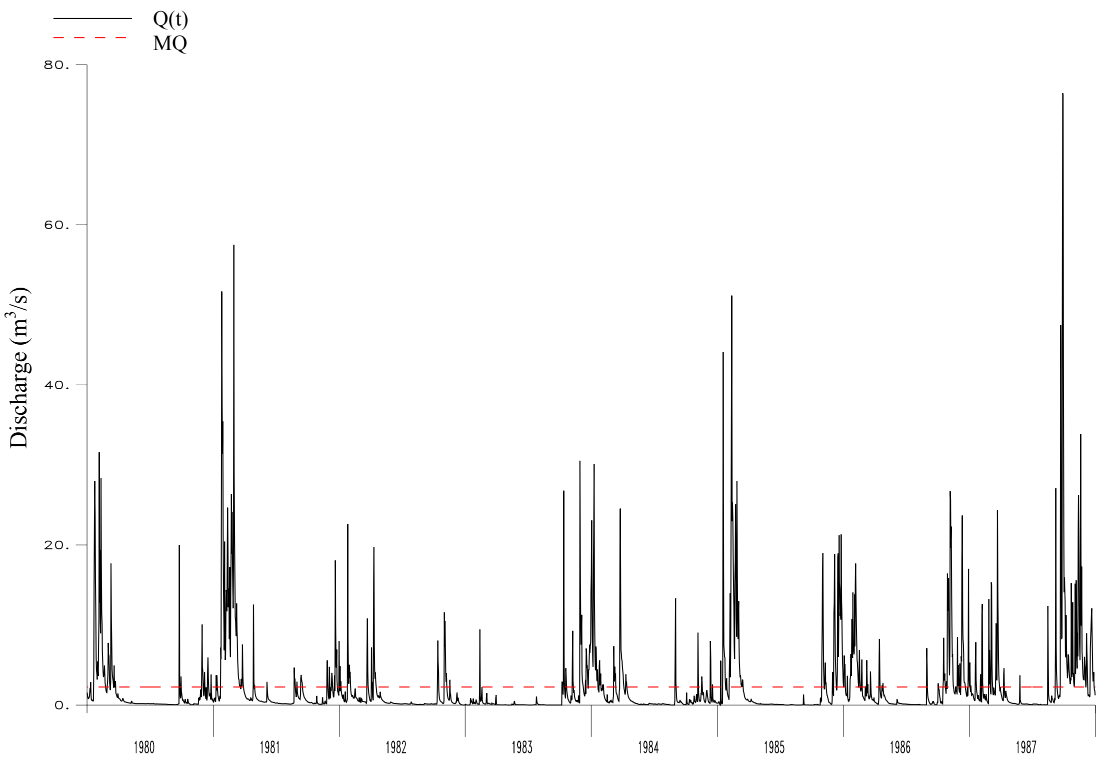
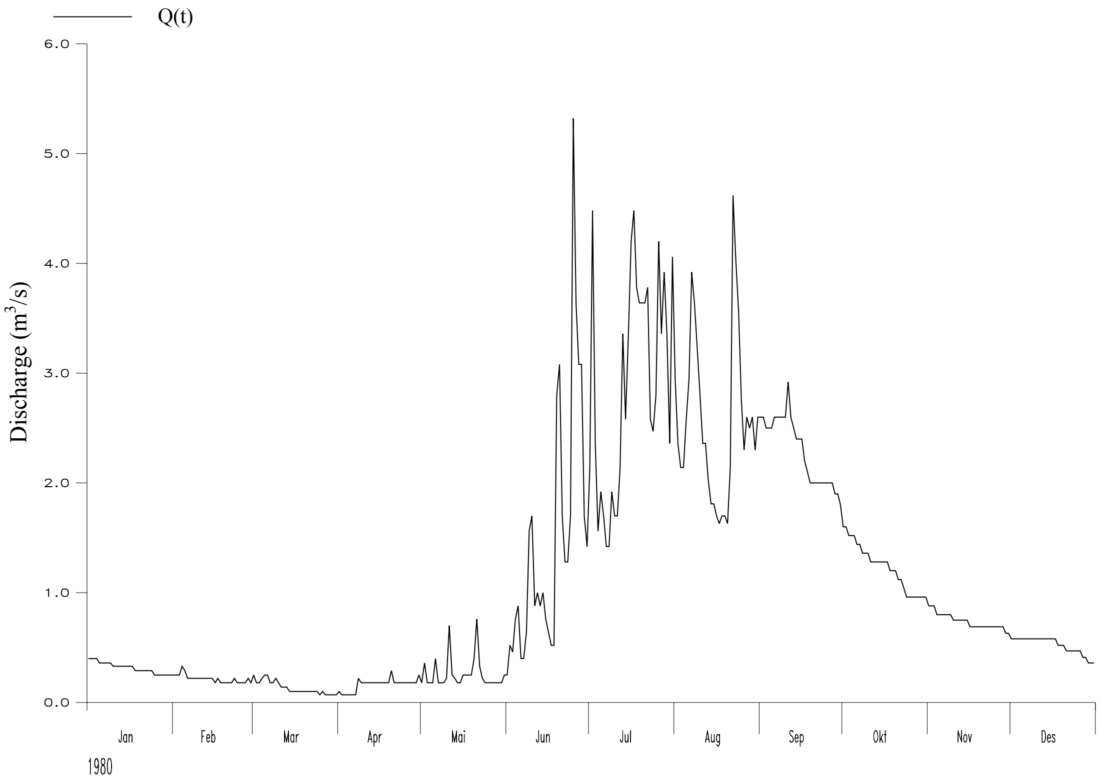


Figure A1.4 Hydrographs of Elands River at Elands River Drift, South Africa. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



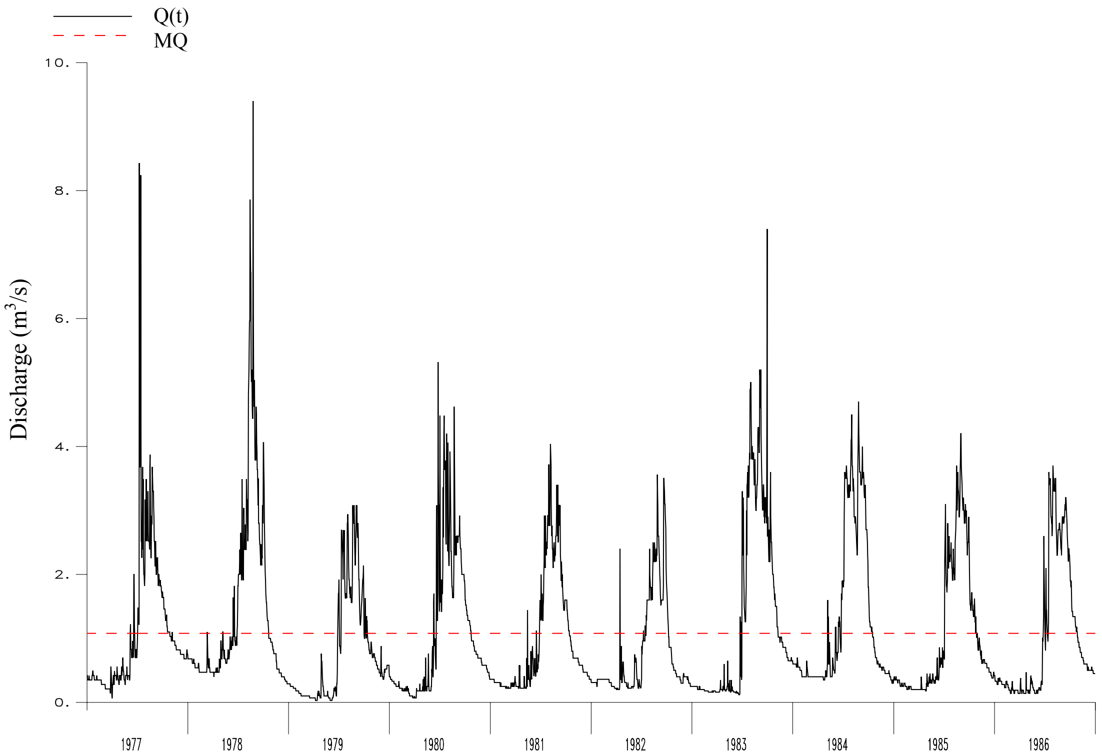
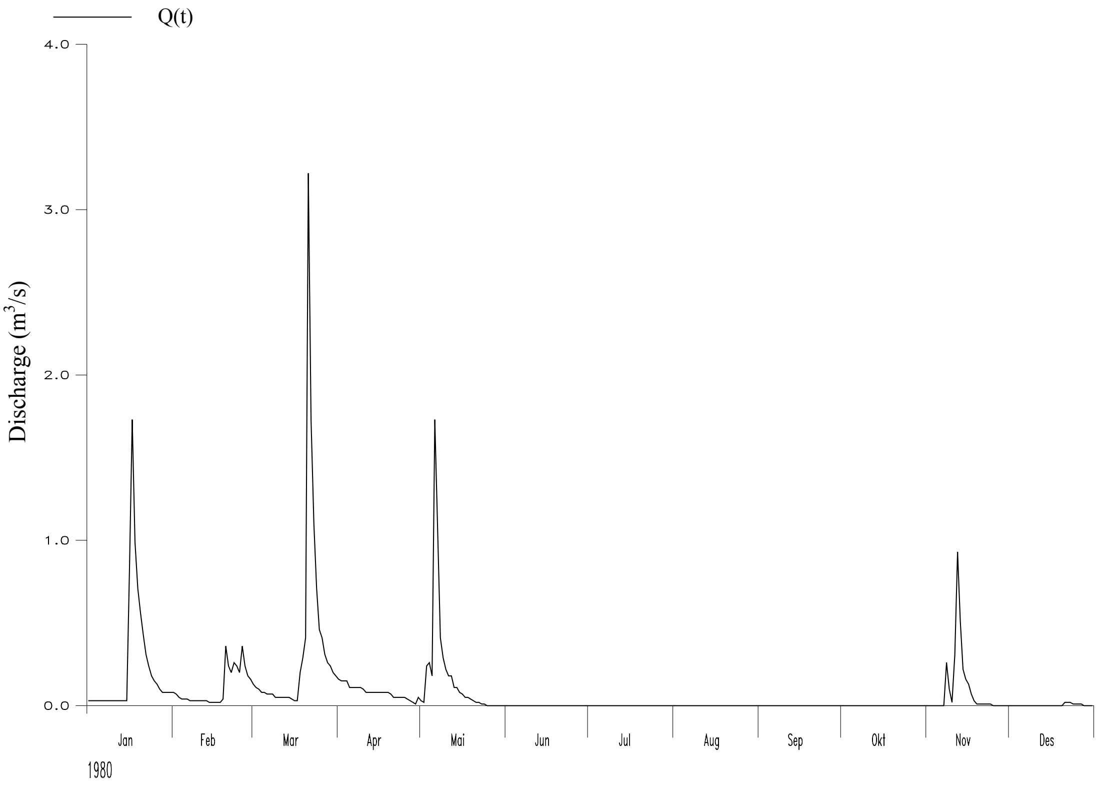


Figure A1.5 Hydrographs of Bagamati River at Sundurijal, Nepal. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1977-1986.



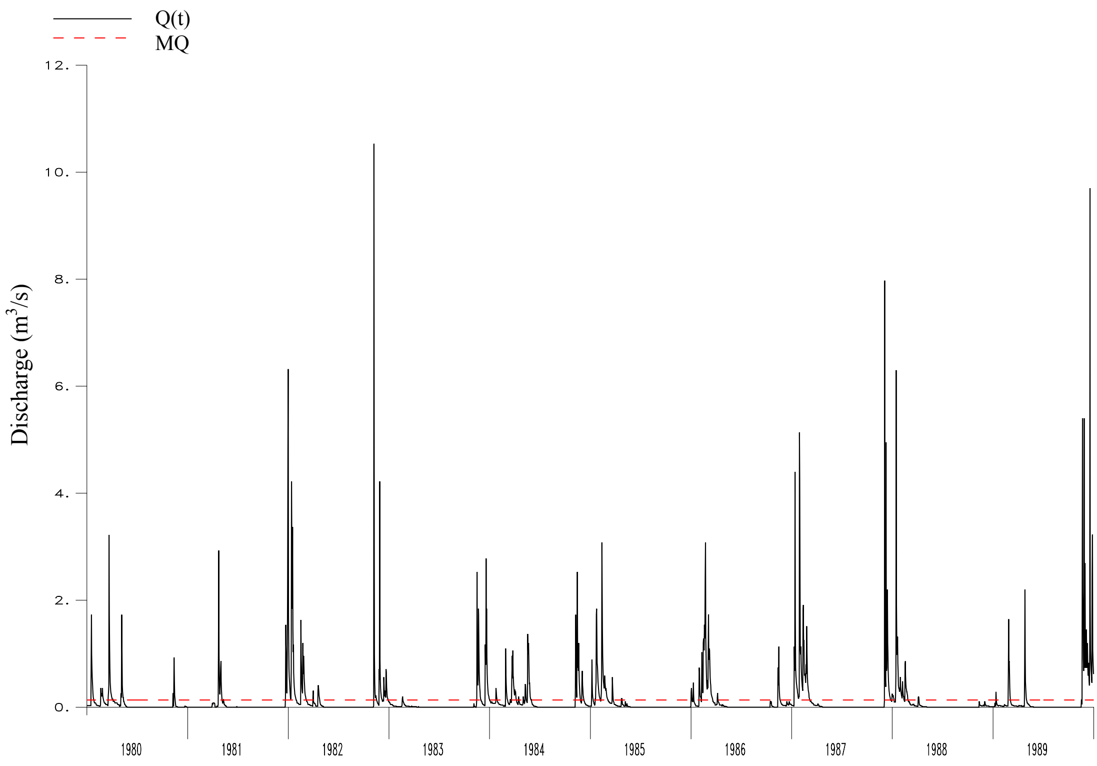
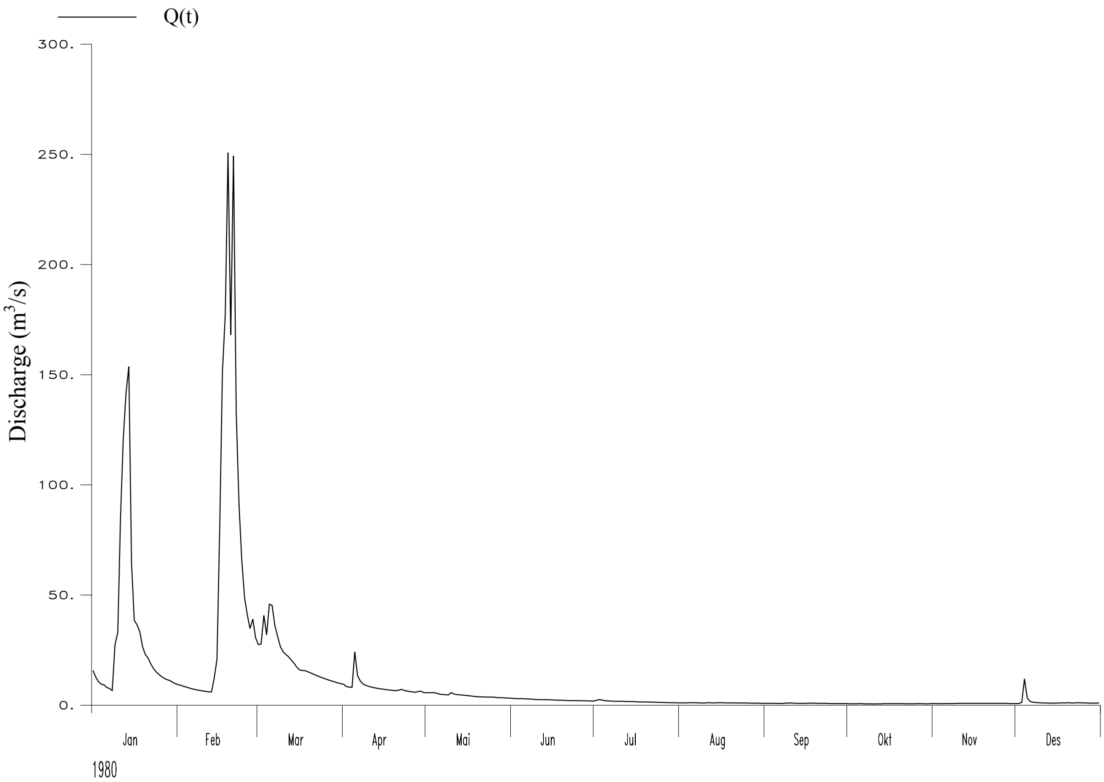


Figure A1.6 Hydrographs of Sabar at Alfartanejo, Spain. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



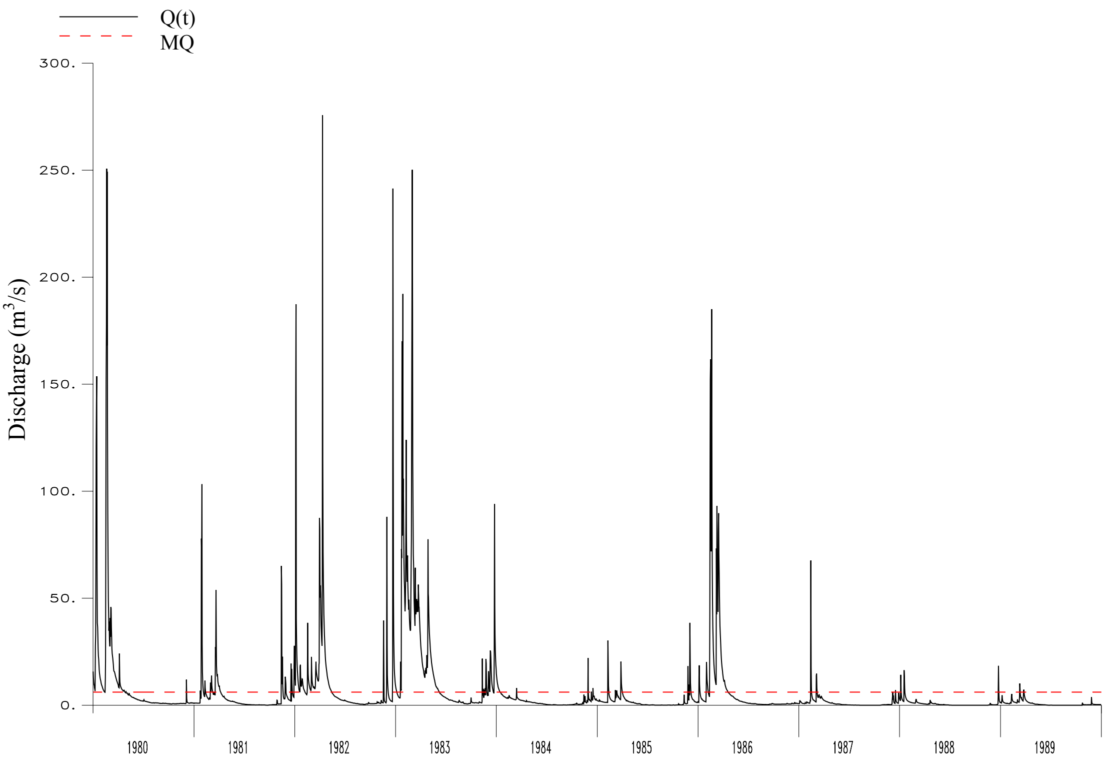


Figure A1.7 Hydrographs of Arroyo Seco at Soledad, USA. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.

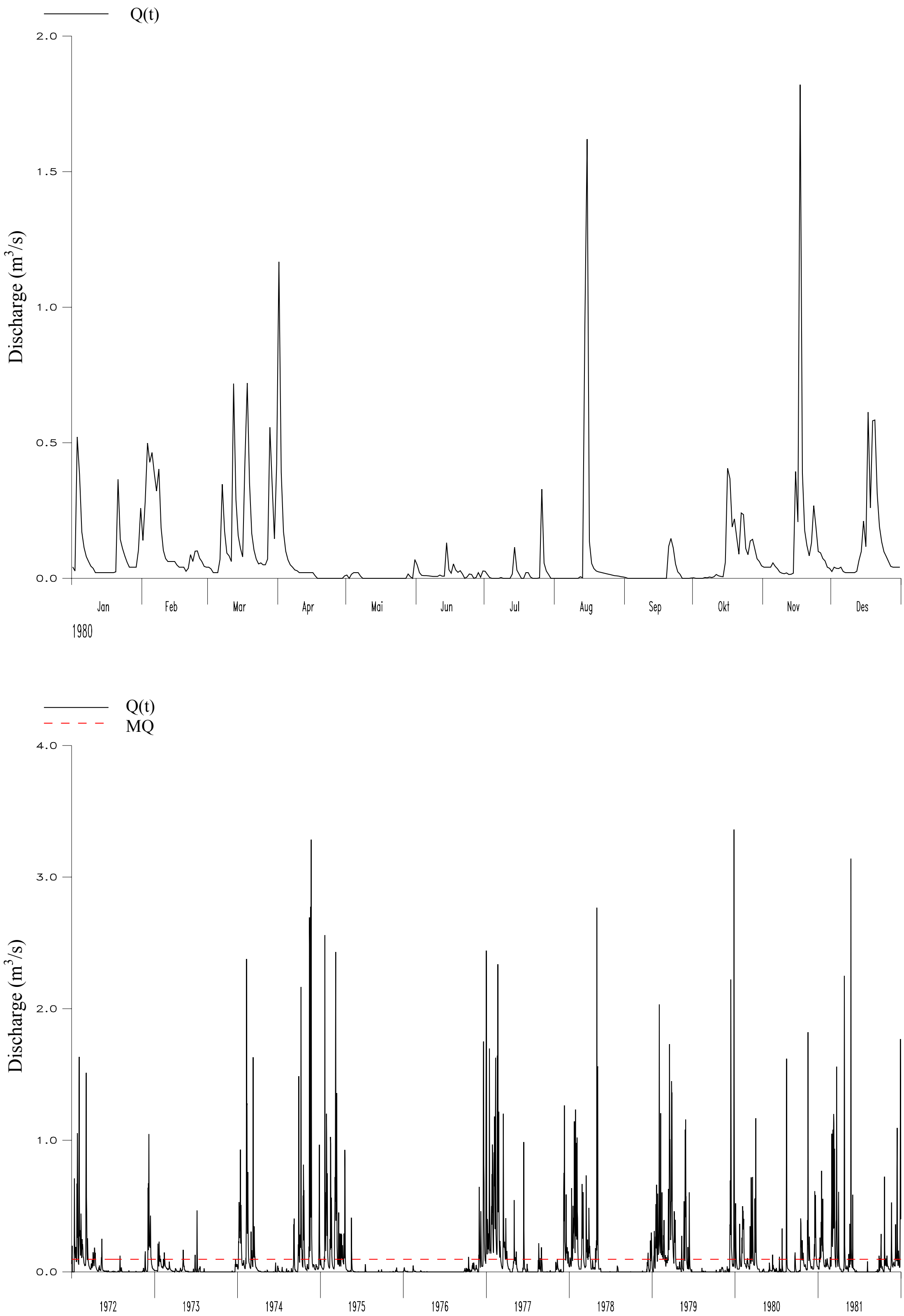
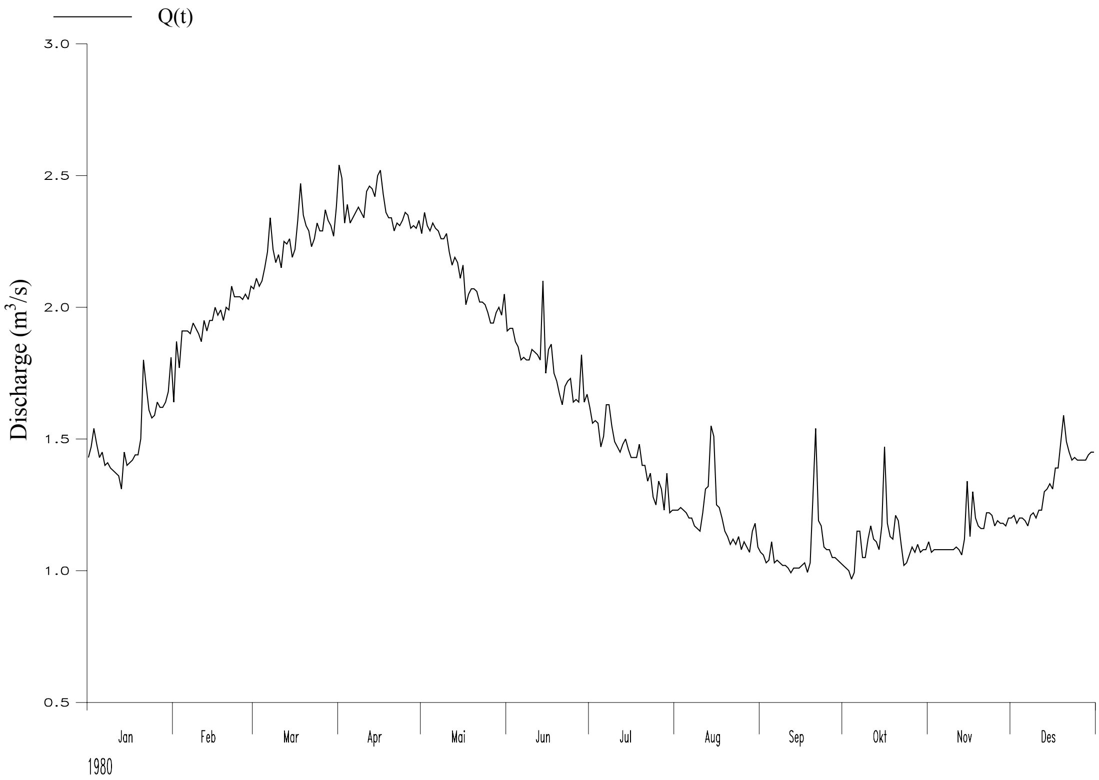


Figure A1.8 Hydrographs of Ray at Grendon Underwood, UK. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1972-1981.



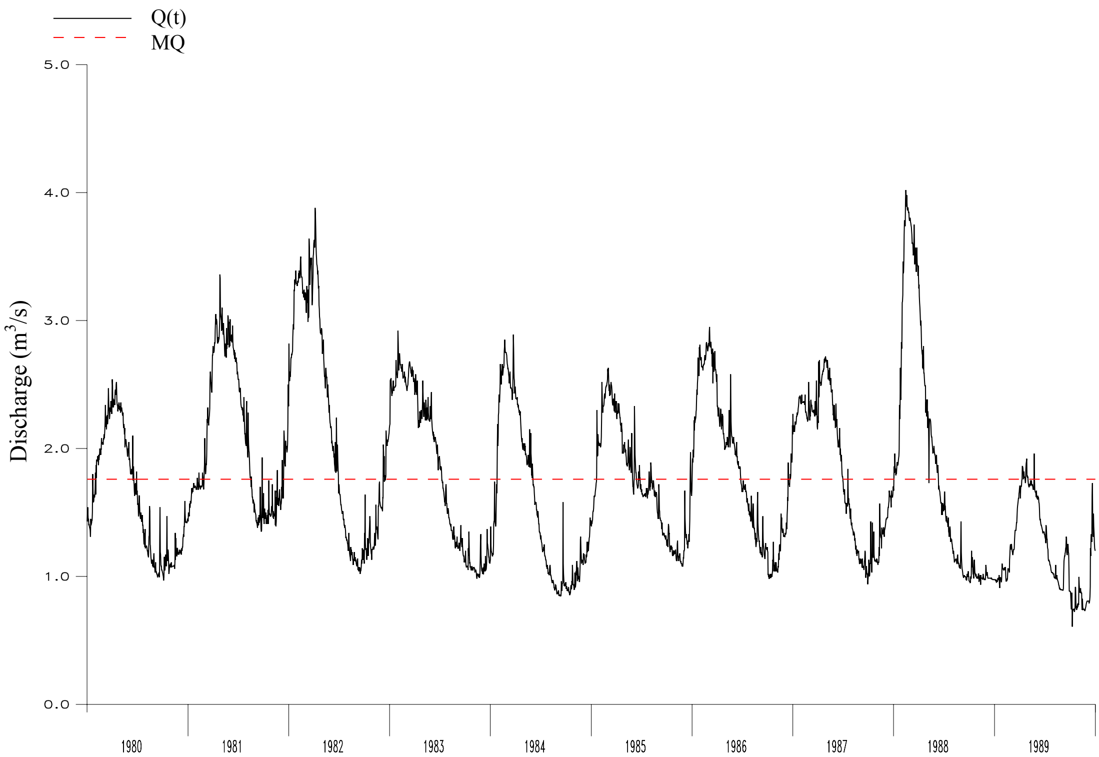
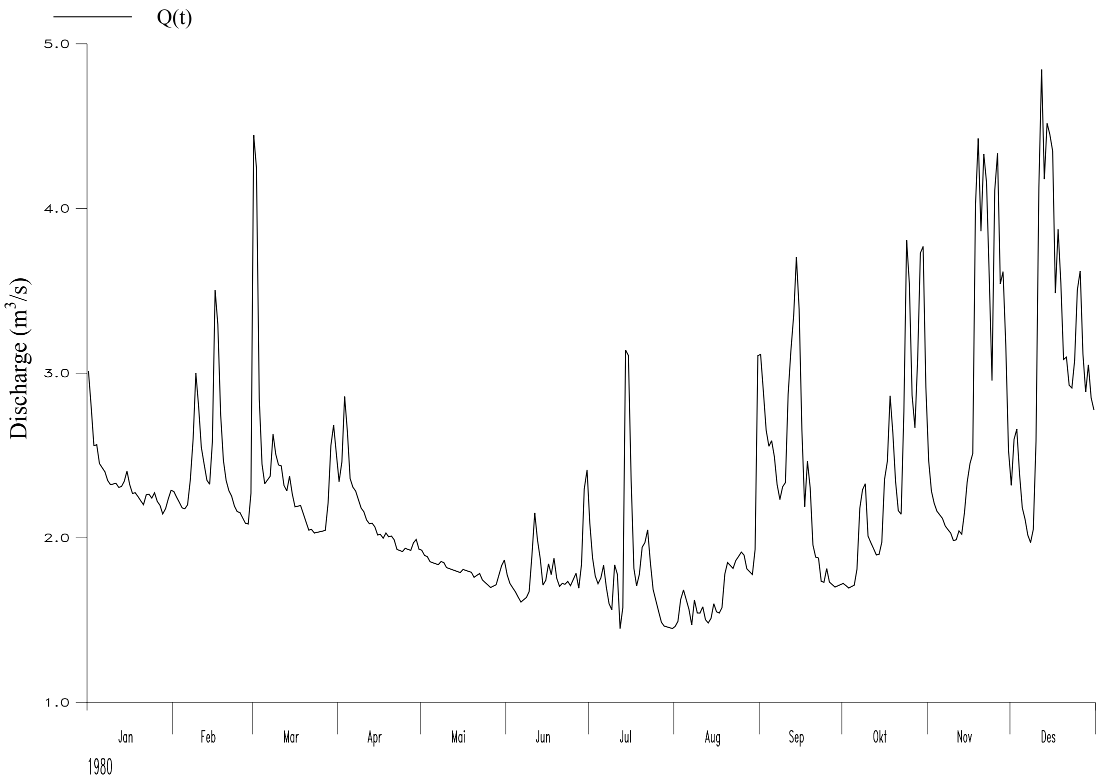


Figure A1.9 Hydrographs of Lambourn at Shaw, UK. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



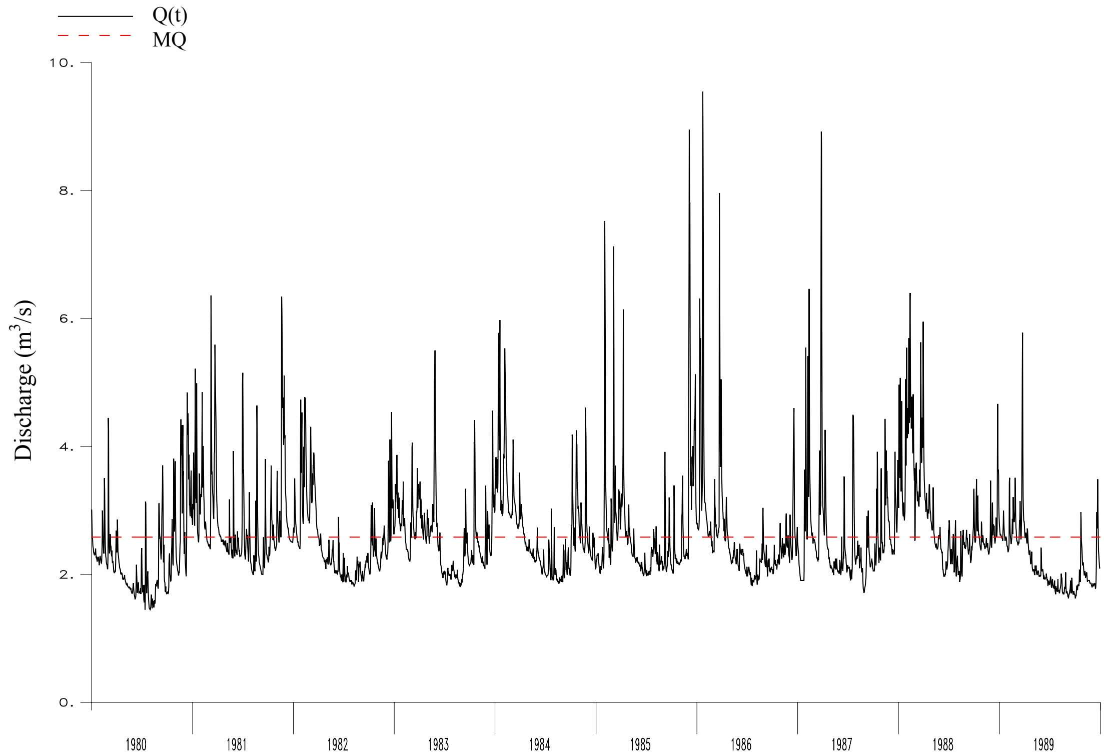
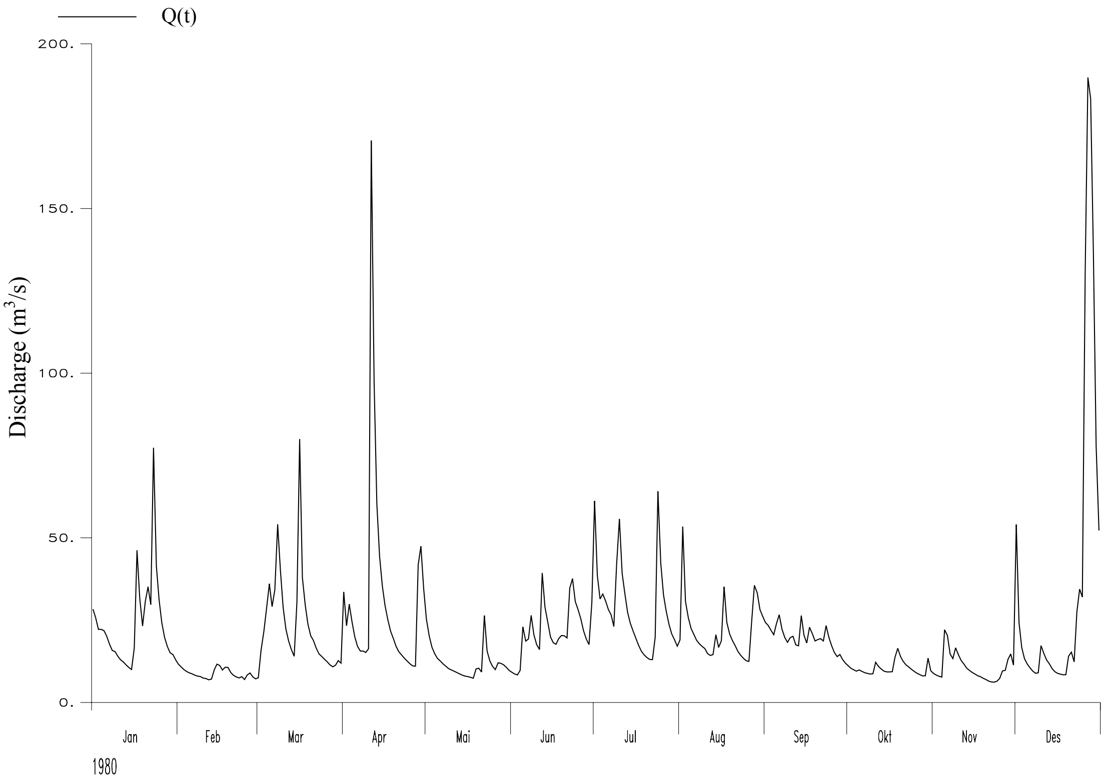


Figure A1.10 Hydrographs of Lindenborg at Lindenborg Bro, Denmark. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



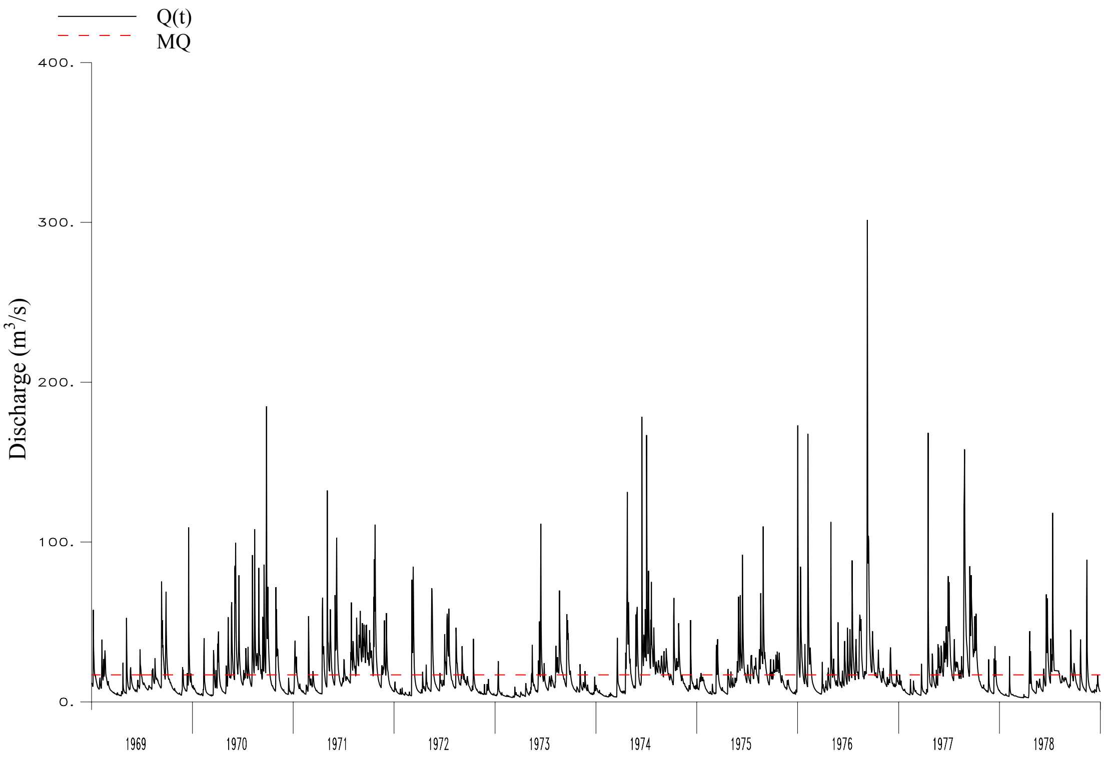
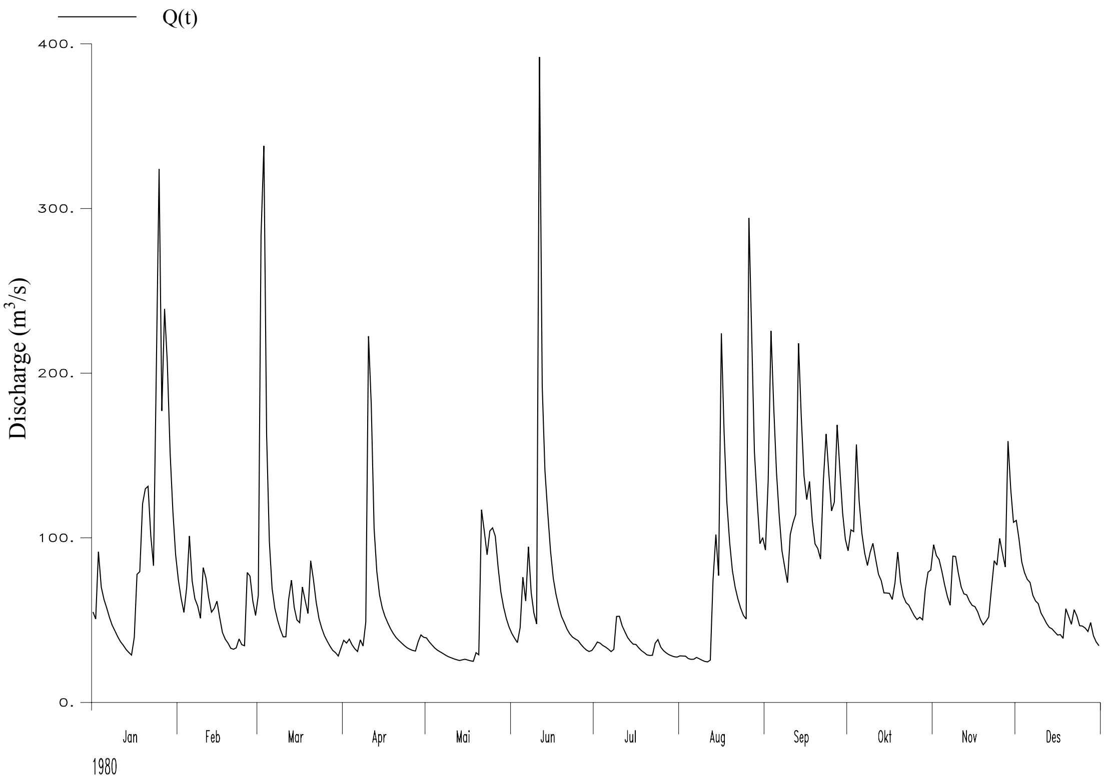


Figure A1.11 Hydrographs of Ngaruroro at Kuripapango, New Zealand. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



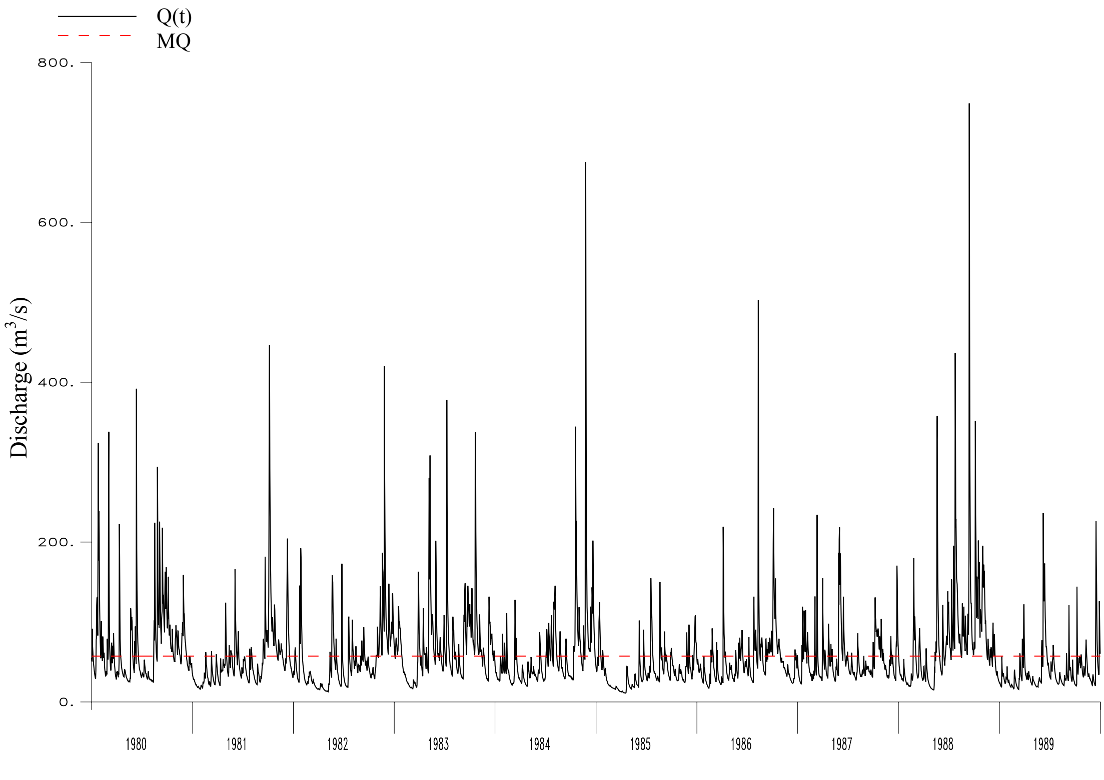
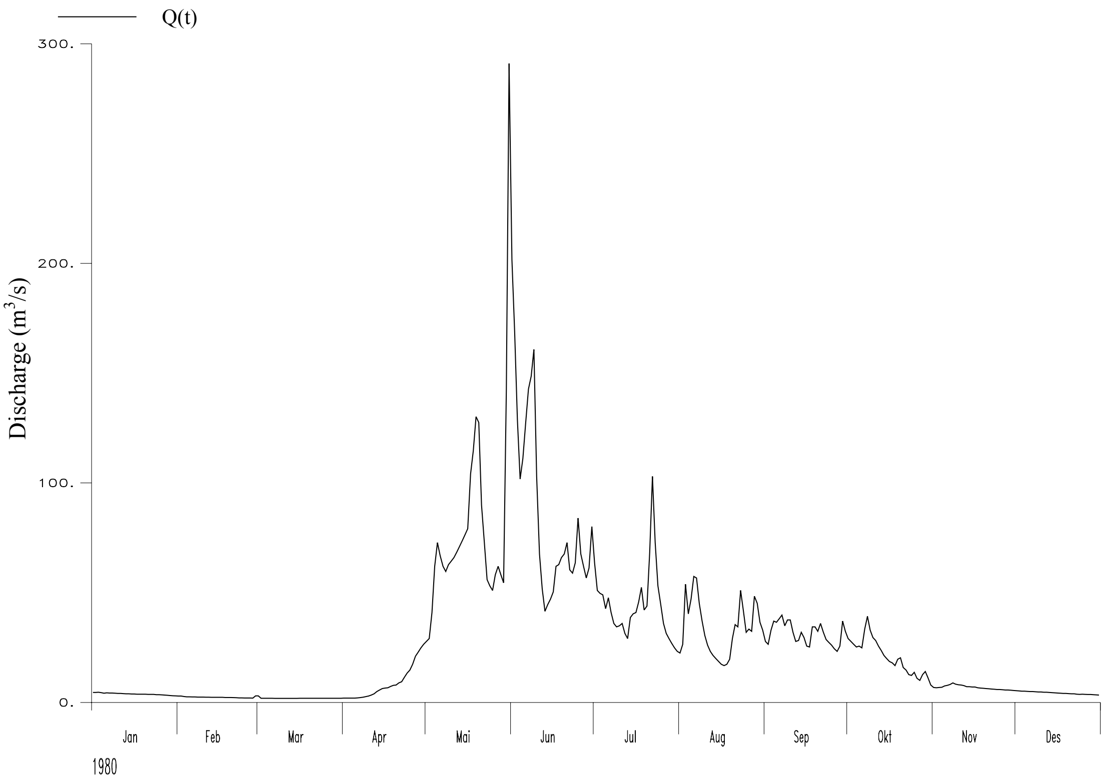


Figure A1.12 Hydrographs of Hurunui at Mandamus, New Zealand. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



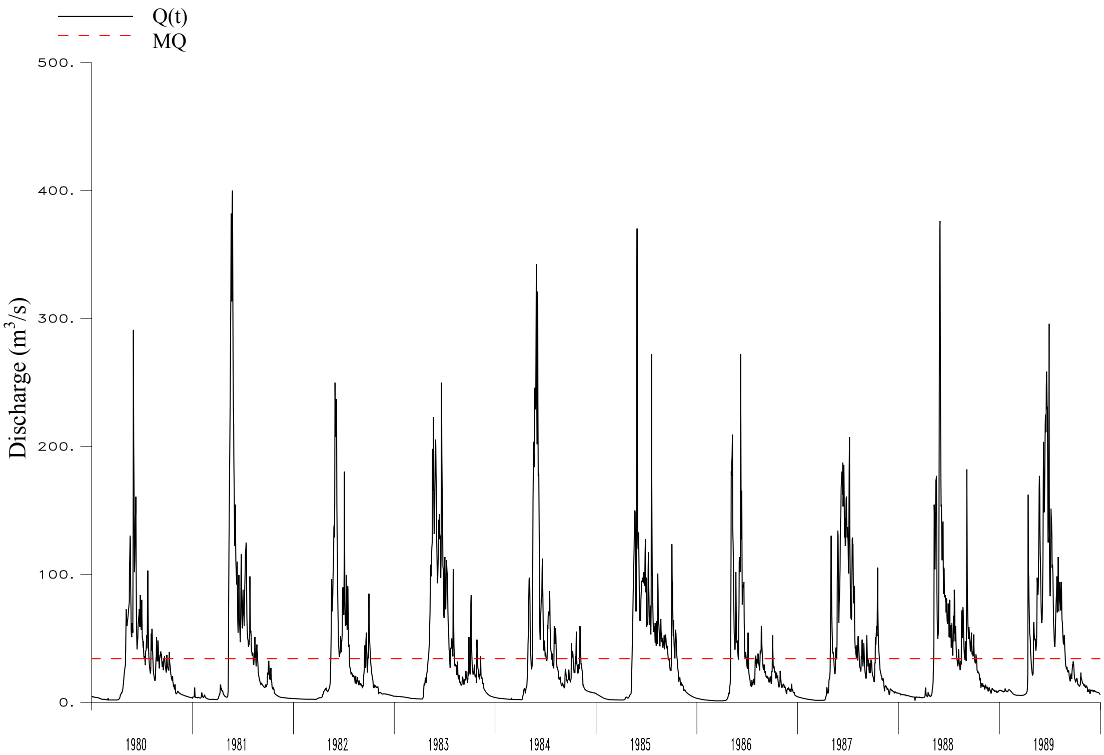
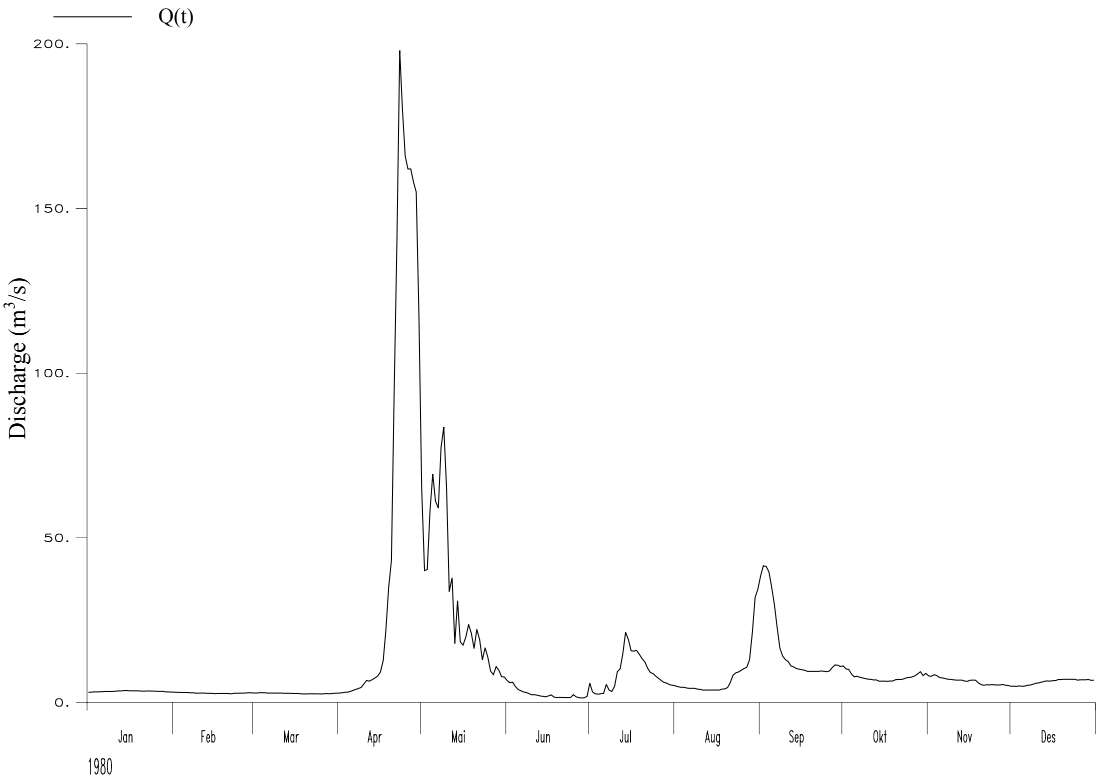


Figure A1.13 Hydrographs of Lågen at Rosten, Norway. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



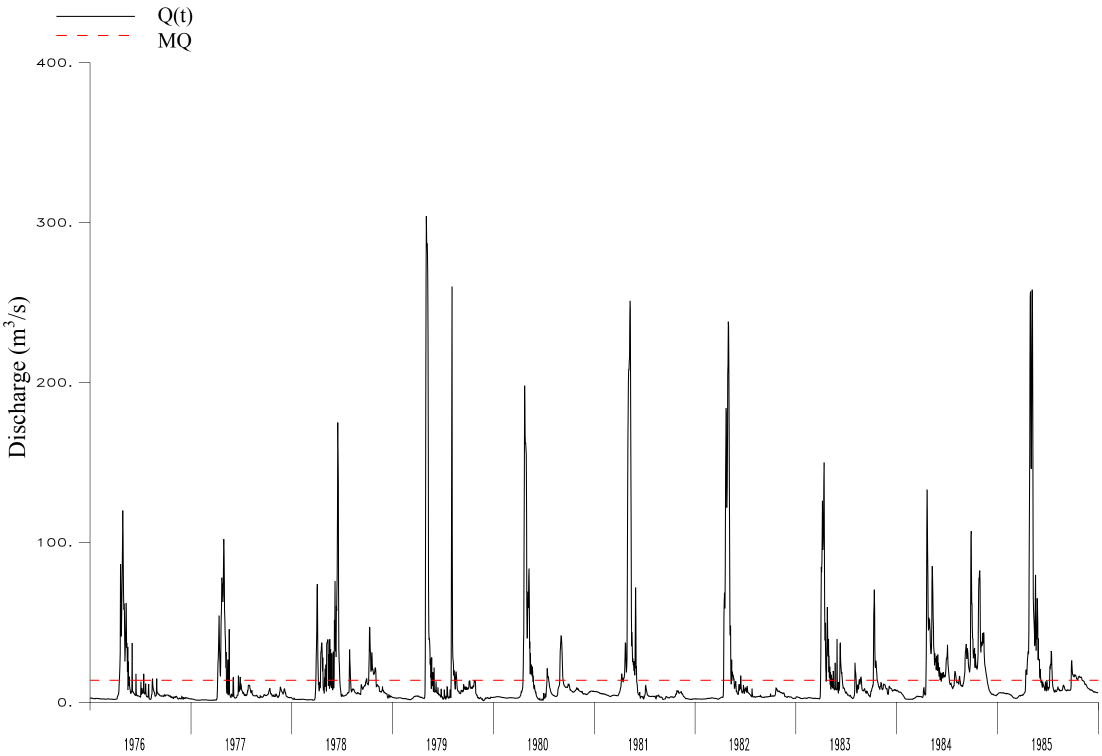
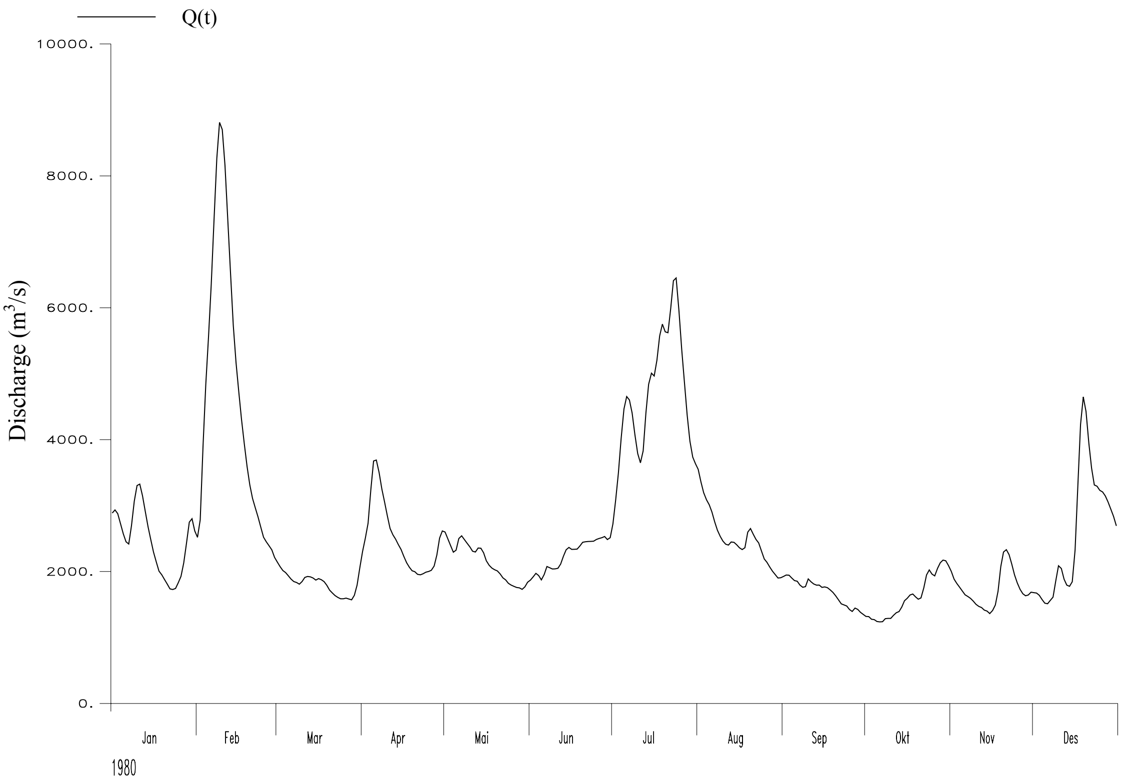


Figure A1.14 Hydrographs of Inva at Kudymkar, Russia. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1976-1985.



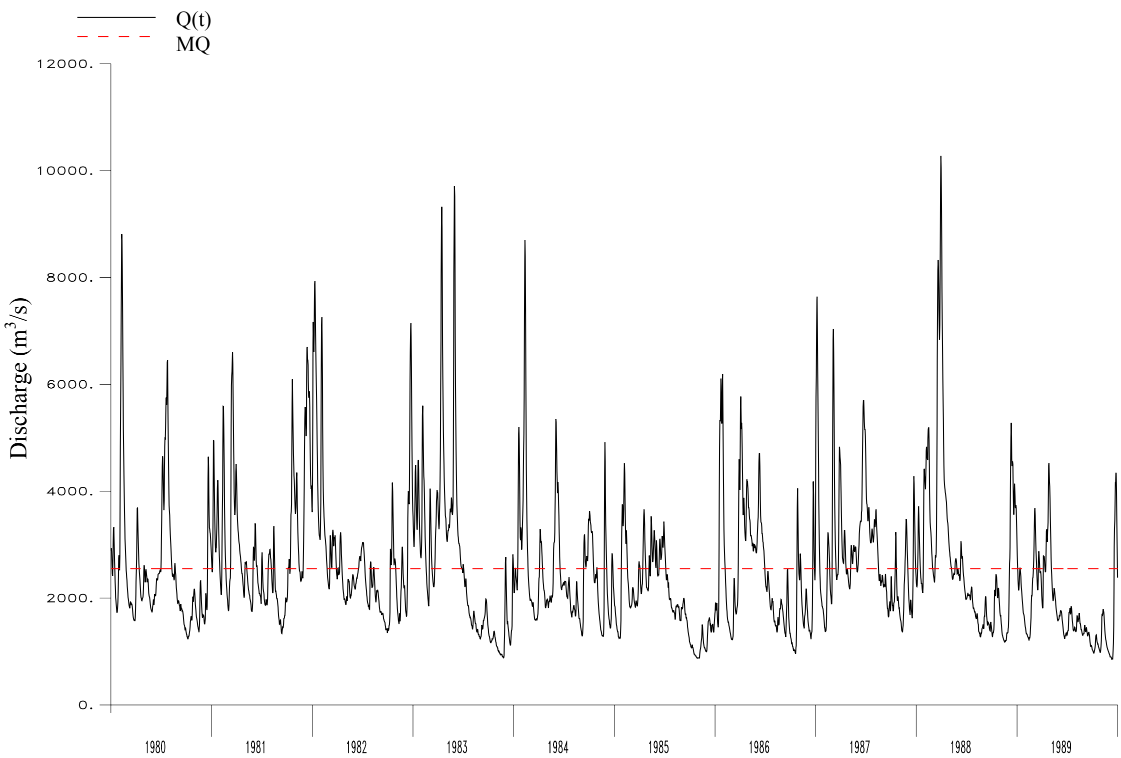
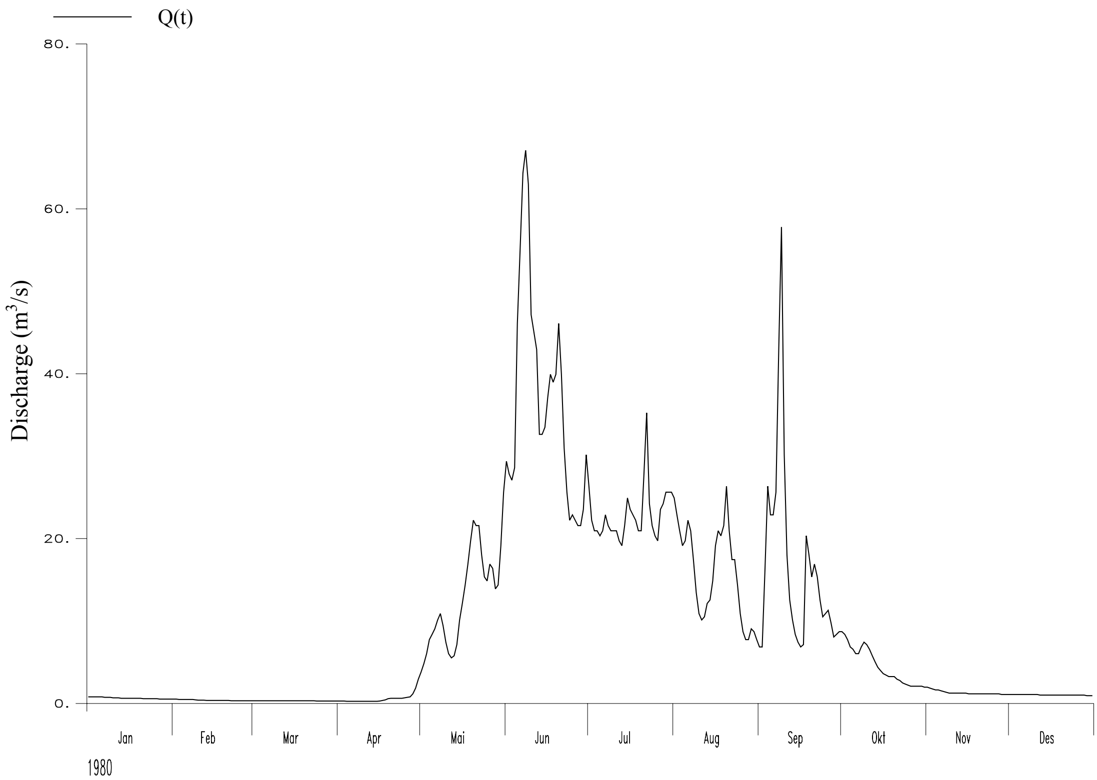


Figure A1.15 Hydrographs of Rhine at Lobith, the Netherlands. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.



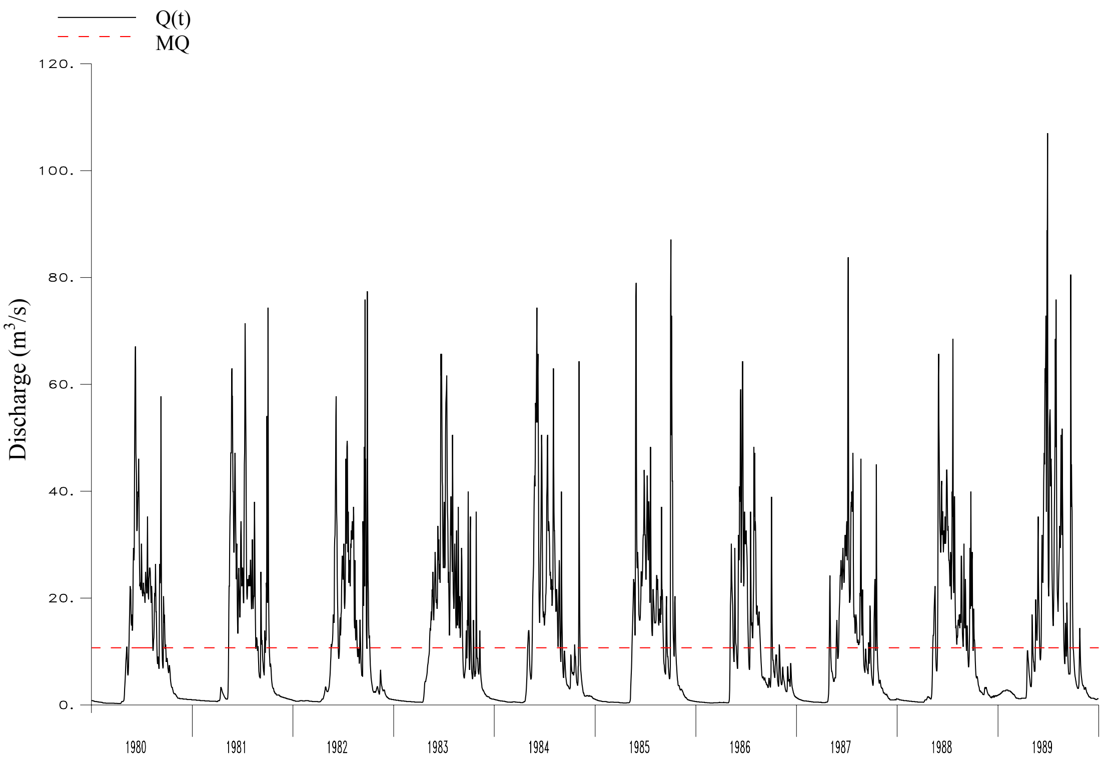


Figure A1.16 Hydrographs of Ostri at Liavatn, Norway. Upper: Daily discharge data from 1980. Lower: Daily discharge data from 1980-1989.

Appendix 2
Results from quality control

Table A2. 1 Results from quality control of the 16 time series from the global data set

River, site and record dates	% missing data	Missing data and problems	Comments	Used years	# of years
Honokohau Stream, Honokohau 1.5.1922-30.91996	2.55	- missing data Nov 1988 to Sep 1990 - shows constant values for more than two weeks also at peaks up to 1934.		1.1.1935 – 31.12.1987	53
Dawib, Dawib 7.12.1978-2.8.1993	3.94	- short record length and missing data in most years	- This is an ephemeral river with zero flow most of the time and occasionally short flow events lasting between one and seven days. Even years without any flow events occur. Most of the recorded flow events occur during Jan-Mar, two minor ones in April and one minor event each in September and December. But also all the missing periods belong to the months Dec-April. ➔ complete years 79, 80 and 87-90	1.1.1987 – 31.12.1990	4 + 2
Pecos River, Pecos 1.1.1930-30.9.1999	0.00	___		1.1.1930 – 31.12.1998	69
Elandrivierie, Elands River Drift 13.12.1963-30.11.1992	9.72	- several periods missing in each year up to 1988, usually including one period longer than 2 weeks	- interpolation of up to 10 days gives 8 years (80-87) that can be used	1.1.1980 – 31.12.1987	8
Bagamati River, Sundurijal 1.1.1970-31.12.1995	2.37	- contains three long missing periods (51, 43, 131 days), - 1.1.1985 shows a one-day-peak of 2,5 m^3/s and 0,35 and 0,4 m^3/s the days before and after, the hydrograph shows short high peaks, but never only for one day, - the series often contains same values (interpolated?) for up to 2 weeks at all flow levels, - it contains also periods with a resolution of only 0,05 m^3/s instead of 0,01 m^3/s otherwise, especially at low flow levels.		1.1.1974 – 31.12.1986	13
Sabar, Alfartanejo 1.10.1963-30.9.1993	0.00	___		1.1.1964 – 31.12.1992	29
Arroyo Seco, Soledad 1.10.1901-30.9.1999	0.00	- shows constant values for over a month at high flow levels in 26, 28 and 30 and for more than a month during low flow throughout the hydrograph, but it is a very flashy river, so constant flow should actually only occur in low flow periods. → has been interpolated? Also in low flow periods?		1.1.1931 – 31.12.1998	68
Ray, Grendon	8.61	- many long missing periods	- there has been a study, showing that in some British	1.1.1963 –	19

Underwood 1.10.1962-31.12.1999			rivers missing values were recorded instead of zero flow. This is a river with no flow periods, but here values are missing at all times of the year and also for very long periods (almost a whole year). The least values are missing in July and the low flow period lasts ca. from June to September.	31.12.1981	
Lambourn, Shaw 1.10.1962-31.1.2000	0.00	- on 8.5.1988 and in September/October 1969 very fast drop downs → looks strange even though it is a permeable catchment. - strange period in October/November 1976.	- the May-88 value (= 1,73 m^3/s) should not affect the analysis too much, since it is only one value and within a middle flow period: > Q(40). - Sep/Oct belongs to the low flow season. The drop-down value on 3.9.69 is 0,78 m^3/s, which is > Q(95) but < Q(90).	1.1.1963 – 31.12.1999	37
Lindenborg, Linden Borg 1.6.1925–31.12.1997	0.00	- missing 16.10.1928 - up to 1960 the series often contains interpolated values for up to 3 weeks at all flow levels.	- Hege didn't use this series for her regional studies, since she was told that this series it not as good as the other Danish series she was using.	1.1.1960 – 31.12.1997	38
Ngaruroro, Kuripapango 20.9.1963-31.12.2000	1.57	- long missing periods (14 – 60 days)		1.1.1967 – 31.12.1978 1.1.1989 – 31.12.2000	12 + 12
Hurunui, Mandamus 27.10.1956- 31.12.2000	0.70	- missing periods of 96 days in 1959, 11 days in 1985 and 6 days in 1988		1.1.1960 – 31.12.2000	41
Lågen, Rosten 27.3.1917-2.5.2003	0.00	- showed zero flow starting 18.7.1997 until the end. But otherwise it never has zero flow → must be 'missing data'.	- Series got updated in NVEs database, and a new Excel file was made (rosten-no_long).	1.1.1918 – 31.12.2002	85
Inva, Kudymkar 1.1.1936-31.12.1995	6.67	- whole years are missing: 86, 88, 90, 93		1.1.1936- 31.12.1985	50
Rhine, Lobith 1.1.1901-31.12.1993	0.00	- on 1.1.1948 it drops down to 777.00 m^3/s, while the days before and after show flows of 6620 and 8400 m^3/s	- 777.00 m^3/s could be a coding for missing values also in the rest of the series → no other 777-values found	1.1.1901- 31.12.1993	93
Ostri, Liavatn 1.1.1965-14.11.2000	0.00	—		1.1.1965 – 31.12.1999	35

Appendix 3
Results from the IC-method

Table A3.1 Summary of drought series for the global data set with $Q_0 = Q70$ (Sabar: $Q_0 = MQ$), pooled with the IC-method without removing minor droughts

Stream	Average no. of droughts per year	No. of multi-year droughts	Percentage of zero-drought years (%)	Mean deficit volume (10^3 m^3)	Maximum deficit volume (10^3 m^3)	Mean duration (days)	Maximum duration (days)
Honokohau Stream	3.8	0	11.3	207.1	2970.0	39	313
Dawib							
Pecos River	1.1	0	22.1	929.0	19457.2	37	310
Elandriverie	2.8	0	0.0	284.7	2462.8	42	226
Bagamati River	1.1	0	13.6	889.3	2743.2	106	203
Sabar (*MQ*)	2.5	1	0.0	1568.0	5370.0	118	387
Arroyo Seco	1.0	0	16.2	1466.7	3896.4	106	269
Ray	2.7	0	7.7	3.0	17.6	43	213
Lambourn	0.9	0	22.2	2259.3	14558.9	124	508
Lindenborg	2.1	0	10.8	1001.1	8503.8	52	254
Ngaruroro	4.1	0	0.0	5667.1	58010.0	29	203
Hurunui	3.1	0	0.0	14310.0	200454.6	24	142
Lågen	1.2	0	31.0	13713	87939.0	22	98
Inva	1.5	0	16.4	3415.2	19556.6	39	143
Rhine (year)	2.3	0	8.7	1344182.1	16330464.0	45	327
Rhine (summer)	1.6	0	17.4	1573911.4	15907968.0	53	326
Ostri	2.0	0	2.9	5603.6	28908.6	15	50

Appendix 4
Results from SPA

Table A4.1 Summary of drought series for the global data set with $Q_0 = Q70$ (Sabar: $Q_0 = MQ$), pooled with the SPA without removing minor droughts

Stream	**Average no. of droughts per year**	**Percentage of minor droughts**	**No. of multi-year droughts**	**Percentage of zero-drought years**	**Mean deficit volume**	**Maximum deficit volume**	**Mean duration**	**Maximum duration**
		(%)		**(%)**	**(10^3 m^3)**	**(10^3 m^3)**	**(days)**	**(days)**
Honokohau Stream	13.6	30.3	0	9.4	45.5	1417.1	7	176
Dawib								
Pecos River	3.3	38.8	0	0.0	690.6	11101.9	25	227
Elandriverie	4.6	34.5	0	0.0	166.7	2207.5	24	189
Bagamati River	1.2	19.2	0	13.6	785.2	2743.2	93	203
Sabar (*MQ*)	0.5	35.7	2	72.4	2198.9	8442.1	270	2004
Arroyo Seco	0.9	9.5	1	16.2	1650.9	4211.1	116.8	556
Ray	5.0	0.0	0	7.7	1.4	16.0	20	188
Lambourn	1.5	56.4	4	22.2	1369.3	18980.5	73	857
Lindenborg	3.2	70.3	1	18.9	425.7	16832.3	34	1787
Ngaruroro	4.9	38.9	0	0.0	4032.0	53748.1	23	200
Hurunui	4.2	40.8	0	0.0	9300.3	200454.6	17	142
Lågen	1.7	28.3	0	7.1	12544.1	87821.1	19	88
Inva	3.4	38.8	0	10.9	1464.0	17953.1	17	145
Rhine (year)	2.0	31.9	4	9.8	1334426.4	18379872.0	52	504
Rhine (summer)	2.1	28.7	0	5.4	1069416.7	13333248.0	40	274
Ostri	3.1	15.4	0	0.0	4318.9	28908.6	11	49