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Geology and Low Flows
What is their relationship?

A case study using storage/yield analysis

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Preface

This report is the result of a five month study at the Institute of Hydrology in Wallingford, UK, which forms part of an MSc-program undertaken through the Agricultural University of Wageningen, The Netherlands. It is a contribution to the FRIEND (Flow Regimes from International Experimental and Network Data) project. The FRIEND research programme is part of the current UNESCO's International Hydrological Programme IV.

I would like to thank my supervisors at the Institute of Hydrology, Dr. Alan Gustard and Gwyn Rees for their help and advice and Dr. Piet Warmerdam and Dr. Henny van Lanen for being my supervisors at the Agricultural University of Wageningen. I would like to thank Karen Irving and Ann Sekulin for providing assistance with the modification of a computer program to undertake the storage/yield analysis. Besides that I would like to thank all the people who are not named for their support during my stay at the Institute of Hydrology.

Data have been used from the European Water Archive. I would like to thank Dr. Alan Gustard for giving me the opportunity to work with these data and I would like to thank Dr. Siegfried Demuth for the SW German data.

Gert Leene
Wallingford, July 1994

Excecutive Summary

The magnitude of low flow response of catchments is closely related to their geology and hydrogeology. Several studies are performed to prove this relationship. The analysis types used in these studies to investigate this relation are mainly based on recession analysis of the recession curves. This study deals with an attempt to look for the relation between low flow behaviour and the geology and hydrogeology of a catchment using storage/yield analysis of river flows.

At the start two geology types were chosen with distinct hydrological characterised differences. Clay catchments were taken as examples of a geology type which is impermeable and has a very low storativity and chalk catchments were taken as examples of a geology type with a high permeability and high storativity. The analysis were first performed for five clay an chalk catchments in the Thames and South Eastern Water Region in the United Kingdom. Probability curves were produced for the development of a certain accumulated deficit volume using annual finite storage/yield failures from semi-infinite turning points. This was done for yields of 80, 60, 40, 20 and where possible 10% of the annual daily flow.

The period of record required to obtain a reasonable storage/yield curve was found to be at least 20-25 years.

The clay and chalk probability curves showed distinct differences. Clay catchments required a bigger volume of storage to provide a certain yield than chalk catchments. The differences between the geology types innitiated a phase in which a wide range of flow regimes was covered. Because catchments do generally not consist of one geology type but of several geology types, the Base Flow Index, which is strongly related to catchment geology, was used as a key to classify the catchments. Nine BFI-classes were chosen. The first class consisted of catchments with a BFI of 0.01-0.15, followed by consecutive classes of 10%. The last class contained the catchments with a BFI ranging from 0.85-0.99. The catchments used are catchments in SW Germany. For every BFI-class averaged curves of the catchments in the class were produced taking the mean of the separate curves of each station. This was done for yields of 80, 60, 40 and 20%. The results show that catchments with BFI's in the higher ranges require less storage to provide a certain yield than catchments with BFI's in the lower ranges.

The same analysis using the same BFI-classification were done for catchments in Switzerland and compared to the results of the analysis in SW Germany. The resulting curves show slight differences between the position of the curves for catchments with BFI's between 0.36 and 0.45 and the differences are smaller for catchments with BFI's ranging from 0.56-0.65.

The differences between the curves within a BFI-class were higher for the higher BFI's and less for the lower BFI's. The same counts for the chalk catchments which have a higher variability than the clay catchments. Clay catchments have a low BFI and chalk catchments have a high BFI.

Assuming that the BFI is closely related to the geology and hydrogeology of a catchment the storage/yield analyses show a clear relation between the occurance of droughts and these catchment characteristics.

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1. Introduction

A drought has many definitions depending on the context and perspective, but a general description might be given as a sustained and regionally extensive occurrence of below average natural water availability, either in the form of precipitation, river runoff or groundwater (Beran & Rodier, 1985). Drought should not be confused with aridity which applies to those persistently dry regions where, even in normal circumstances, water is in short supply. In addition to the hydrological elements of a drought meteorological and agricultural factors may also be significant in prolonging a drought, all of which have an impact on society and the economy. However the scope of this study is to consider only the low flow component of a drought.

Low river flows may occur as a result of a sustained lack of rainfall. During such periods base flow is the main flow component in catchment with groundwater storage. The reduction in flows can be compounded father by the impact of artificial influences in terms of direct abstractions and discharges from and to the rivers and the indirect influence of groundwater abstraction on the flow regime of a river. In order to undertake low flow analysis it is important to have a proper data set for the analysis. Not only artificial impacts may influence the quality of the data set but also the accuracy with which the lower discharges are measured. Not all gauging stations provide reliable flow data at low water stages.

Several studies have been carried out to investigate relations between geological features of catchments and the low flow behaviour of these catchments. Examples of earlier studies showing relations between catchment geology and hydrogeology and low flow behaviour include Wright (1970 and 1974), who introduced a Geology Index determined by regression analyses. Periera & Keller (1982) used regression analysis to find recession parameters for basin discharge during the agricultural growing season, lasting from approximately April to October. They studied the influence of basin characteristics on the three flow components direct flow, subsurface flow and base flow using a multiple regression analysis. They showed that the hydrogeology of the catchment was the main factor influencing subsurface and base flow. Gustard et al. (1992) linked a hydrogeological response of soils to low flow response of catchments in UK. Also Gustard & Irving (1993) linked low flow response to the CEC soil classification for Europe. Demuth & Hagemann (1993) regionalised base flow in SW Germany applying a hydrogeological index. In their study the recession constants of summer and winter recession curves were key parameters in the classification.

This study uses storage/yield analysis to investigate the influence of catchment geology on low flows.

The objectives of the study are:

- To generate average storage/yield curves for five clay catchments and five chalk catchments;

- To study a possible relation between the storage/yield curves and the catchment geology;

- To compare average storage/yield curves of catchments with different BFI's assuming a relation between BFI and catchment geology;

- To compare average storage/yield curves of catchments with similar BFI's in different regions/countries.

The study was carried out for catchments from the UK, SW Germany and Switzerland using catchment and flow data from the European Water Archive.

Chapter 2 describes the methodology of storage/yield analysis (Section 2.1) and a selection of catchments will be given which are used for the analyses (Section 2.2). Chapter 3 presents the results of the analyses and discusses the results. Chapter 4 contains the conclusions and recommendations.

2. Methodology

2.1 Introduction

A great number of methods is available for characterising or defining the frequency of low flows. Beran & Rodier (1985) present a comprehensive survey of the wide range of techniques used for describing the hydrological aspects of drought. For an individual drought Hamlin & Wright (1978) describe three approaches for identifying the development of the drought and assessing its severity. The UK Low Flow Studies Report (Institute of Hydrology, 1980) presents three main reasons for the increased number of analysing techniques of low flows:

1. Different definitions of a low flow event: an event can be described in terms of a threshold discharge, an accumulated volume, a length of time spent below a threshold or a rate of recession;

2. Different methods of expressing frequency: the frequency or probability may be thought of as a proportion of time, e.g. flow duration curve, or as a proportion of years in which a given low flow occurs, e.g. flow frequency curve;

3. Different durations or averaging periods: many applications consider low flow not at an instant but averaged over some period of time such as seven days or six months.

Table 2.1 summarises a selection of low flow measures, the regime properties they describe, the data employed in their calculation and their application.

During droughts water resources management is important to assure water supply to all consumers and organisations dependent on water. The use of storage reservoirs for water supply during droughts is common. It provides water when rivers are not able to supply a certain yield. This study is performed to get an idea of the sensibility of reservoirs in relation to the geological characteristics of the catchments which feed the rivers flowing through the reservoirs.

Table 2.1 Summary of low flow measures

Low flow measure	Property described	Data employed	Application
Flow duration curve	Proportion of time a given flow is exceeded	Daily flows or flows averaged over several days, weeks or months	Licensing abstractions or effluents, hydropower General hydrological description
Flow frequency curve (annual minimum)	Proportion of years in which the mean discharge over a given duration is below a given magnitude	Annual minimum flow - daily or averaged over several days	Return period of drought Design of major schemes First step in some types of storage yield analysis
Low flow spells (duration of deficiency periods)	Frequency with which the flow remains continuously below a threshold for a given duration	Periods of low flows extracted from the hydrograph followed by a statistical analysis of durations	More complex water quality problems such as fisheries Amenity Navigation
Deficiency volumes	Frequency of requirement of a given volume of make-up water to maintain a threshold flow	As for spells except the analysis focuses on the volume below the threshold	Regulating reservoir design
Storage yield	Frequency of requirement for a given volume of storage to supply a given yield	Daily flows or flows averaged over several days or monthly flow	Preliminary storage yield design Review of yield from existing storage
Time to accumulate runoff volume	Time to accumulate a given volume of runoff with a given frequency of occurrence	Accumulated runoff volume starting at different points of the year	Probability of reservoir refill in drought conditions
Recession constant	Rate of decay of hydrograph	Daily flows during dry periods	Short term forecasting General hydrological description Hydrogeology studies

(Gustard et al., 1992)

2.2 Storage/yield analysis

In Figure 2.1 a simple example of a reservoir storage capacity / yield problem is illustrated. Form a river with a stream flow sequence Q(t) a controlled release sequence, or yield, Y(t) is extracted to supply a demand area. If the stream flow sequence Q(t) can not supply the requested yield Y(t) a reservoir with active storage capacity C adds water to sustain the requested yield Y(t) until the reservoir storage is depleted. When the stream flow Q(t) exceeds the yield Y(t) the reservoir storage will start to replenish. When the reservoir is full the excess water of the stream flow Q(t) over the yield Y(t) is spilled in the river down stream of the reservoir.

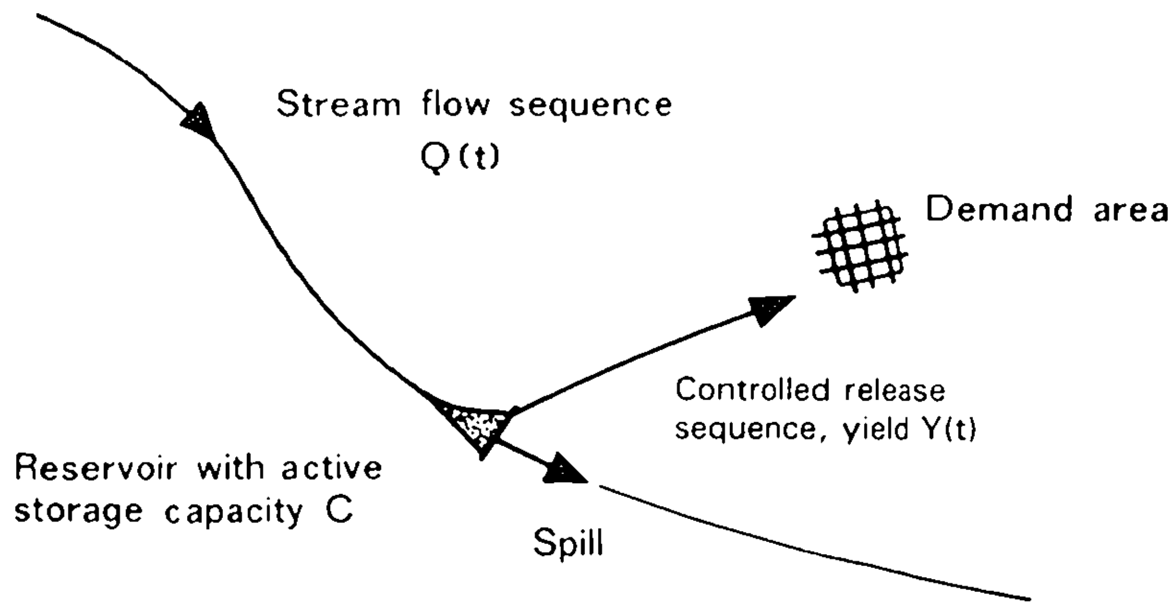

Figure 2.1 A reservoir storage/yield problem (McMahon & Mein, 1986)

For storage/yield analysis of single storage reservoirs, several procedures can be used. McMahon & Mein (1986) classify these procedures theoretically into three main groups. The first group (critical period techniques) includes methods in which a sequence (or sequences) of flows for which demand exceeds inflows is used to determine the storage size. The second group consists of methods based on the probability matrix, and methods based on stochastic data generation are included in the third group.

The analysis which will be used in this study are part of the group of critical period techniques. The analyses are performed for yields of 80, 60, 40, 20 and where possible for 10 % of the average daily flow. First a description of several semi-infinite and finite storage failure methods will be given, followed by a motivation for the choice of one of the analysis types.

Possible methods can be distinguished into five different types:

1. Semi infinite event based spell volumes
2. Semi infinite annual maximum spell volumes
3. Finite event based storage failures
4. Finite annual maximum storage failures
5. Finite storage analysis using semi infinite turning points.

ad 1 A semi-infinite storage, such as used in the semi-infinite event based spell volumes procedure, is a storage which expands and contracts to exactly the right volume to just maintain a given yield through a period of low river flow. It can therefore never empty, but it can spill once flow has exceeded yield for long enough to allow the storage to be replenished. An event is therefore defined as the period of time from the start of a deficit (when flow first falls below yield) until the moment that the deficit is completely replenished. Every event will therefore have a storage requirement associated with it. It is these storage deficits ranked in order of size which form the basis of the analysis. The semi-infinite storages represent the real volumes of storage which are required to sustain a yield.

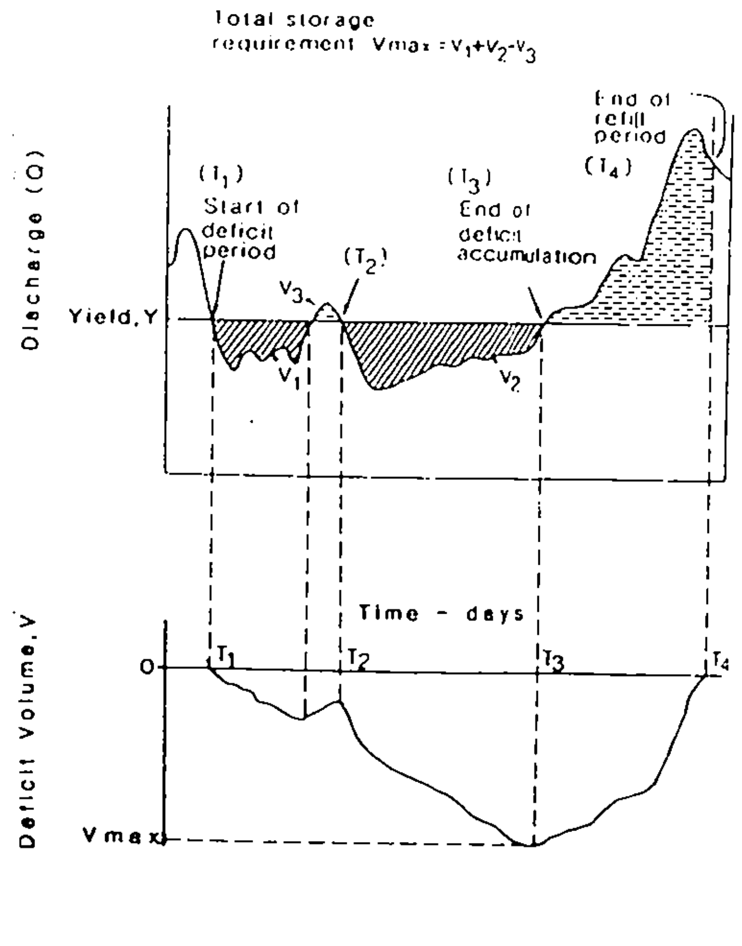

Figure 2.2 Definition of semi-infinite storage/yield analysis (Brown, 1991)

The definition of semi-infinite storage/yield analysis is presented in Figure 2.2. From the river flowing into the filled reservoir with a discharge Q a certain yield Y is extracted. At time T_1 the river flow falls below the yield level and a deficit volume starts to develop. The accumulation of the deficit volume can be given as:

$$\text{Volume of Deficit}_i = \Sigma(Q_i - Y_i)$$

where:

Q_i = discharge of the river at the point of the reservoir at day i [m^3/day]
Y_i = extraction of water from the reservoir at day i [m^3/day]

At a certain point the flows exceed the yield required and the deficit volume is partly replenished. At T_2 though a further development of the deficit volume starts until the maximum deficit volume is reached at T_3. At this point the refill of the reservoir starts and the deficit volume is fully replenished at T_4. The event as described by this type of analysis starts at T_1 and ends at T_4 when the deficit volume is fully replenished.

ad 2 Annual maximum semi-infinite storage/yield analysis is used as a method of determining the proportion of years requiring a storage greater than or equal to any given storage. The largest deficit noted on any one day in each year of flow data is recorded. The largest deficit volumes of each year are represented by V_1 - V_{10} in Figure 2.3. These deficits are then ranked and assigned plotting positions, assuming they are independent events. Events are independent if one event does not influence the existence of another event.

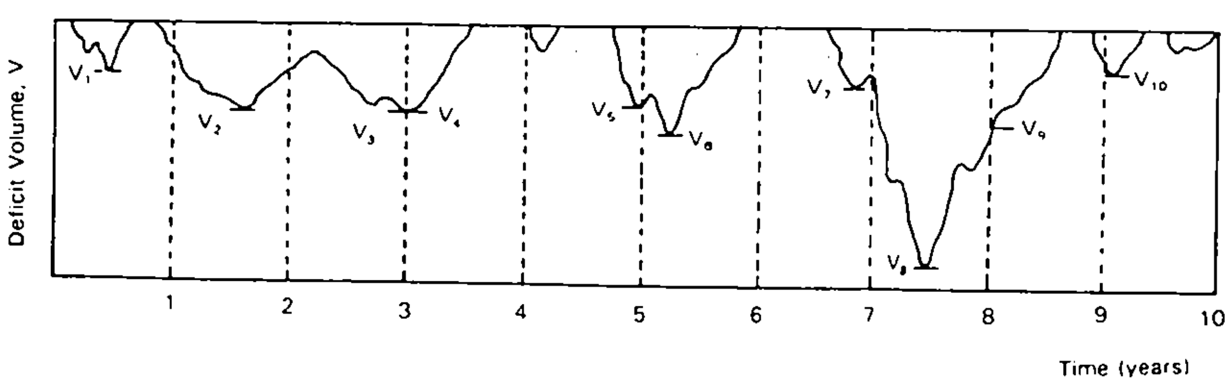

Figure 2.3 Definition of annual maximum semi-infinite storage/yield volumes

Semi-infinite events as defined in ad 1 can last over one or more years. This can take place when large yields are extracted or in dry years. In this case the annual maximum deficit is no longer always necessarily the maximum deficit encountered in an event. The increase and decrease of the deficit volume can coincide with the end of a year. For the purpose of this analysis the event is considered to be ending at the end of the year and the remaining deficit at the end of the year will be carried over to the next year.

ad 3 Finite event based storage/yield failure analysis entails running through the daily inflow series to a reservoir with an assumed storage of pre-defined volume and modelling its behaviour while extracting a constant yield from it. The reservoir has a finite volume, therefore pumping a yield from the reservoir which is greater then the natural inflow will cause the stored water to be depleted and in severe circumstances the reservoir will empty or 'fail'. An event is defined as the failure of a reservoir and its complete replenishment. The number of 'failures' each pre-defined storage experiences is counted (up to one per event) and this is used to determine the frequency of failure of that storage.

ad 4 Annual maximum finite storage/yield failure analysis is the finite storage version of semi-infinite annual maximum analysis. Because the method uses pre-defined finite storages, each of which has been run through with the whole record of mean daily flows, each year has a list of storages which have failed in it. The largest storage found to fail in each year is noted, and the number of years in which each of these storages was found to fail is then counted. The probability of failure is the percentage of years of the period of record for which the storage failed.

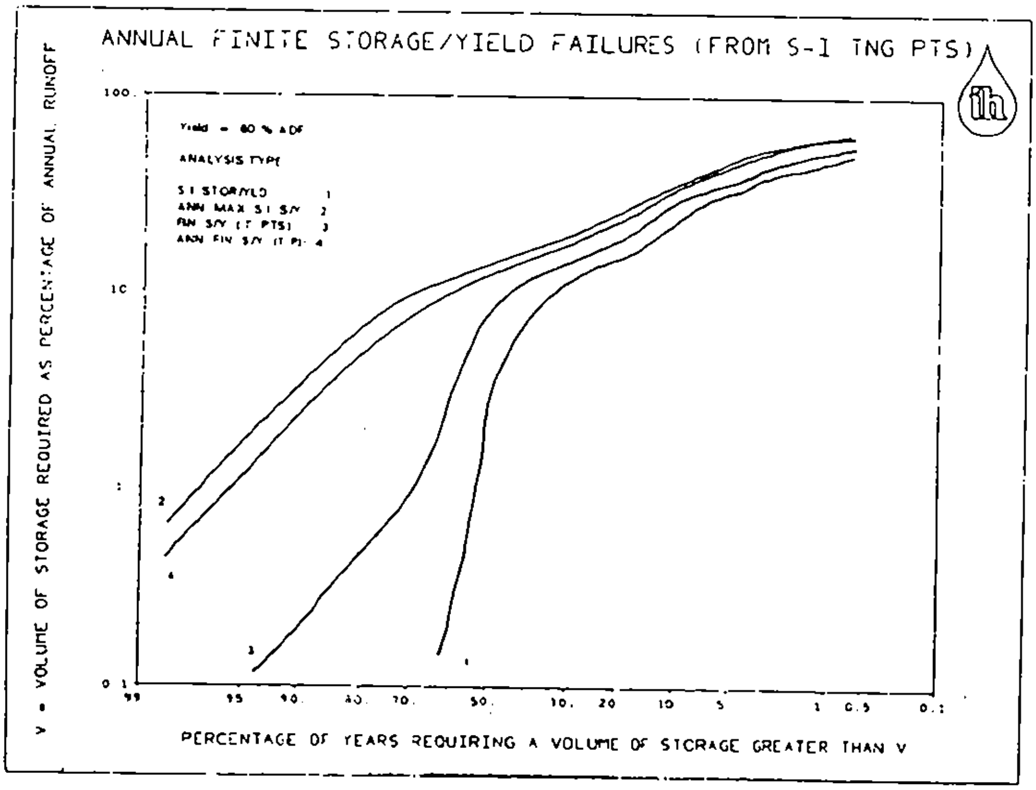

Figure 2.4 Influence of different analysis types on curve position

ad 5 The final technique for storage/yield analysis is a combination of semi infinite event based analysis and finite storage/yield failure analysis. The semi-infinite storage/yield analysis as described in ad 1 provide storages required to just sustain a given yield. These calculated semi-infinite storage volumes represent the pre-defined storages of finite reservoirs used as an input for the finite storage/yield failure analysis. The failures of these pre-defined storages are referred to as 'turning points' because they represent the exact size of a finite reservoir which would just fail. These turning points can be used in both the finite event based storage failure analysis (ad 3) and the finite annual maximum storage failure analysis (ad 4). These storages volumes, when plotted, give a true representation of the probability at which they are plotted. This is not true for the finite analysis with the random chosen storage reservoirs volumes.

Each of this methods has its advantages and disadvantages. The major advantage of the annual based methods is that there is no need to apply an assumed distribution in order to convert event-based probability to annual-based probability. The plotted curves of the different analysis types are shown in Figure 2.4. On the x-axis the percentage of years is given which requires a volume of storage V to provide a certain yield. On the y-axis the required volume of storage V is given as a percentage of the annual runoff. For example if we apply the annual maximum semi-infinite storage/yield analysis (ad 2) then in 80% of the years a storage volume of 5% of the annual runoff is needed to provide a yield of 60% of average daily flow. The Poisson distribution as used in the past for the event based probability (curves 1 and 3) has a major impact on the position of the curves. The annual series can be assumed to be normally distributed (curves 2 and 4). Because the event based analysis require an assumed Poison distribution to convert event based probabilities into annual based probabilities, the annual series which are already assumed to normally distributed are believed to provide a better representation of the probabilities.

A disadvantage of the annual-based analyses is the fact that by only taking the largest events, with the limitation of 30 semi-infinite storages, the occurrence of smaller events stay hidden.

Brown (1991) has concluded that, taking in account the advantages and disadvantages of all the methods, the finite analysis with semi-infinite reservoirs gives the best representation. It represents the probability that a certain storage is needed, on an annual basis, to be able to provide a defined yield to a demand area. Besides that the method does not use an assumed distribution. Therefore this analysis type is selected for this study.

2.3 General selection criteria

In order to maintain the integrity of the results from any analysis, the quality and length of the dat record are important. In particular gauging stations should be free of errors and should represent natural flow regimes. For the purpose of this study, gauging stations in the UK, Germany and Switzerland which possessed good quality data, as defined by a 'low flow flag' in the European Water Archive (Gustard et al., 1989) with at least 20 years of data were used.

2.3.1 Selected stations

Different criteria were applied to the gauging stations to identify sub-sets based on geology to select catchments overlying predominantly chalk or clay geological units with a further subdivision based on the BFI. Chalk has a high storage capacity and has a high secondary permeability. Clay is impermeable or has a very low permeability and has a low storage capacity. The effect of these characteristics on the flow regimes is shown in Figure 2.5 a and b. The clay catchments show a flashy flow regime. The base flow component of these catchments is low, indicated by Base Flow Indices (BFI's) between 0.15-0.45 (Institute of Hydrology, 1980) . In Appendix A a description is given of the derivation method of the BFI. On the other hand the chalk catchments respond smoothly to excessive rainfall. The BFI ranges roughly from 0.90-0.98 (Institute of Hydrology, 1980) . To increase the distinction the chalk catchments are selected on a BFI, higher then 0.90 and clay catchments are selected on a BFI lower then 0.30. In Table 2.2 the BFI's of different geological units as defined in the Low Flow Studies Report (Institute of Hydrology, 1980) are shown.

Table 2.2 *Typical Base Flow Indices for various rock types*

Dominant Permeability Characteristics	Dominant Storage Characteristics	Example of rock type	Typical BFI range
Fissure	High storage	Chalk	0.90 - 0.98
		Oolitic limestone	0.85 - 0.95
	Low storage	Carboniferous limestone	0.20 - 0.75
		Millstone Grit	0.35 - 0.45
Intergranular	High storage	Permo -Triassic sandstones	0.70 - 0.80
	Low storage	Coal measures	0.40 - 0.55
		Hastings Beds	0.35 - 0.50
Impermeable	Low storage shallow depth	Lias	0.40 - 0.70
		Old Red Sandstones	0.45 - 0.55
		Silurian / Ordovician	0.30 - 0.50
		Metamorphic - Igneous	0.30 - 0.50
	No storage	Oxford Clay Weald Clay London Clay	0.15 - 0.45

(Institute of Hydrology, 1980)

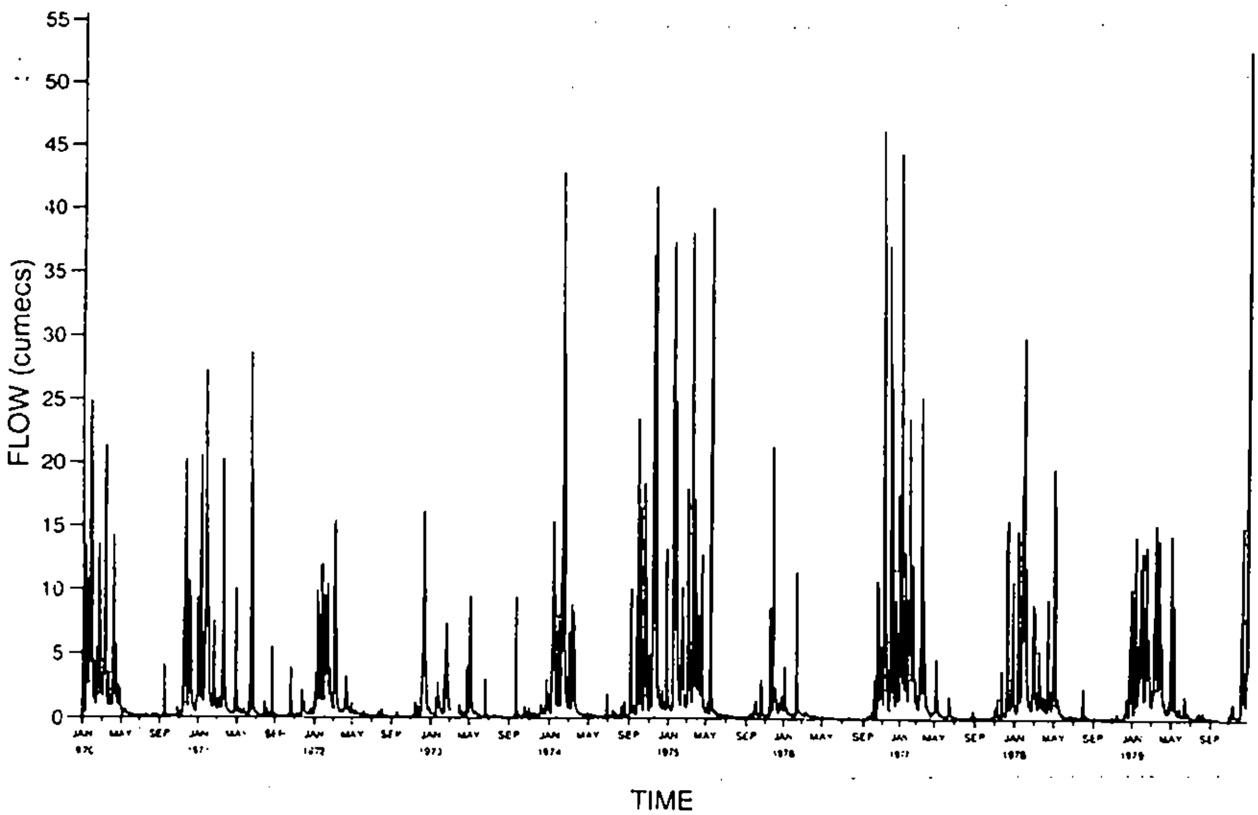

Figure 2.5a Flow regime of a clay catchment

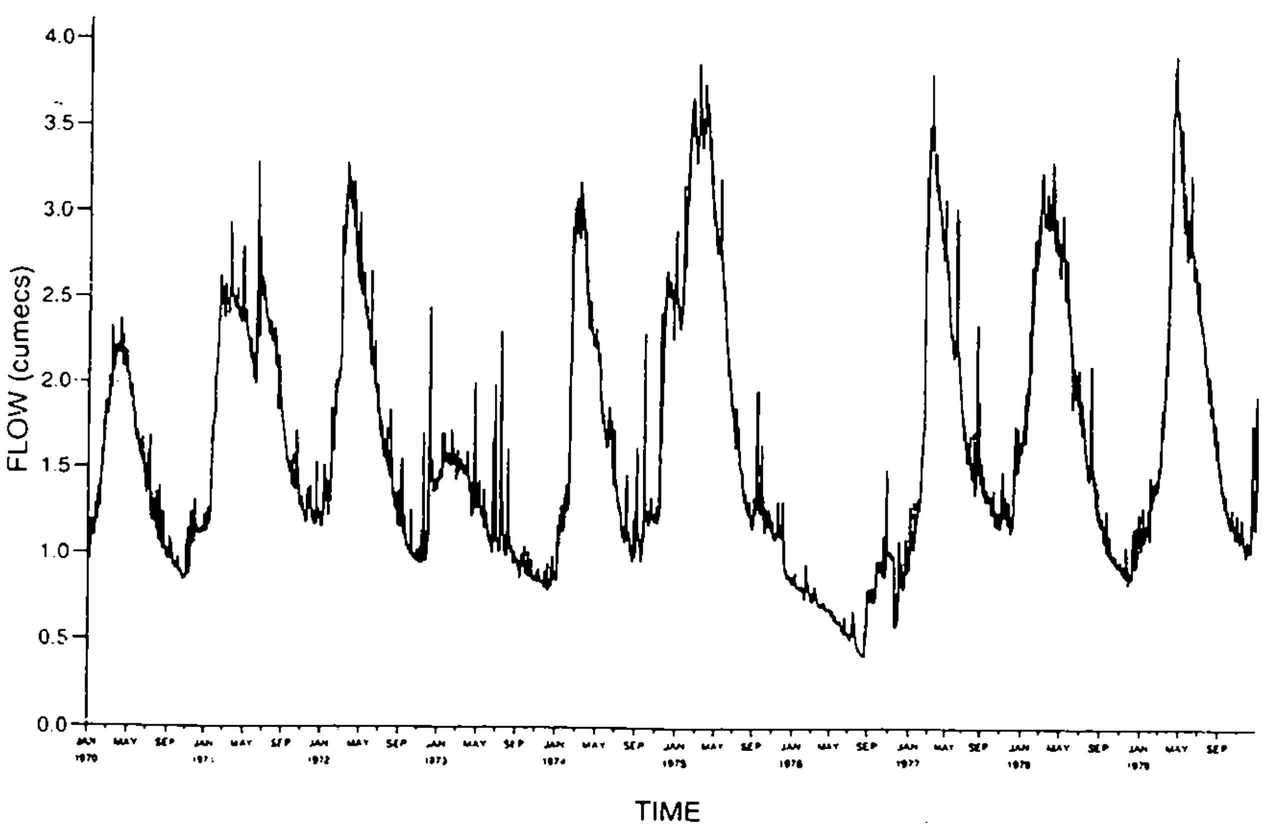

Figure 2.5b Flow regime of a chalk catchment

The geological characteristics of a catchment are rarely restricted to a single geology type, but are more commonly represented by a number of geological units which may be very different in terms of hydrogeological response. Therefore a second set of selection criteria was applied to the gauging stations to identify sub-sets based on the Base Flow Index, representing the hydrological response of catchments as a result of complex geologies. For the classification the BFI's of the catchments are divided in nine classes as shown in Table 2.3. The standard curves are the result of averaging curves in a BFI-class. Every standard curve is the result of averaging curves of at least four gauging stations. The average curves are supposed to represent a region.

The classification was done for catchments in State of Baden-Wurtemberg in SW Germany because a wide range of geology types was available in this region causing a wide range of BFI's.

Table 2.3 *BFI-classes*

Class	BFI-range	Class	BFI-range	Class	BFI-range
A	0.01-0.15	D	0.36-0.45	G	0.66-0.75
B	0.16-0.25	E	0.46-0.55	H	0.76-0.85
C	0.26-0.35	F	0.56-0.65	I	0.85-0.99

A final selection criteria was applied to gauging stations in the state of Baden-Wurtemberg and Switzerland in order to identify catchments in mountainous and non-mountainous regions in order to assess the influence of snow accumulation and to illustrate differences between climates, using BFI to classify the catchments.

The regions of the catchments which are selected for the analyses of the different stages in the research are shown in Figure 2.6. Appendix B gives the periods of record of the selected stations.

2.3.2 Pooled and averaged curves of selected station groups

The storage/yield analysis using the finite reservoir storage approach based on semi-infinite defined storages was applied on the numbers of stations given in Table 2.4 to identify storage/yield curves for individual stations. The curves of the individual gauging stations are then pooled and averaged for each geological class or BFI-class.

Table 2.4 Number of gauging stations used in each sub-set

Country	Selection criteria	Number of stations
United Kingdom	Clay catchments	5
	Chalk catchments	5
SW Germany	BFI 0.36 - 0.45	7
	BFI 0.46 - 0.55	10
	BFI 0.56 - 0.65	8
	BFI 0.66 - 0.75	8
	BFI 0.76 - 0.85	4
Switzerland	BFI 0.36 - 0.45	8
	BFI 0.56 - 0.65	4

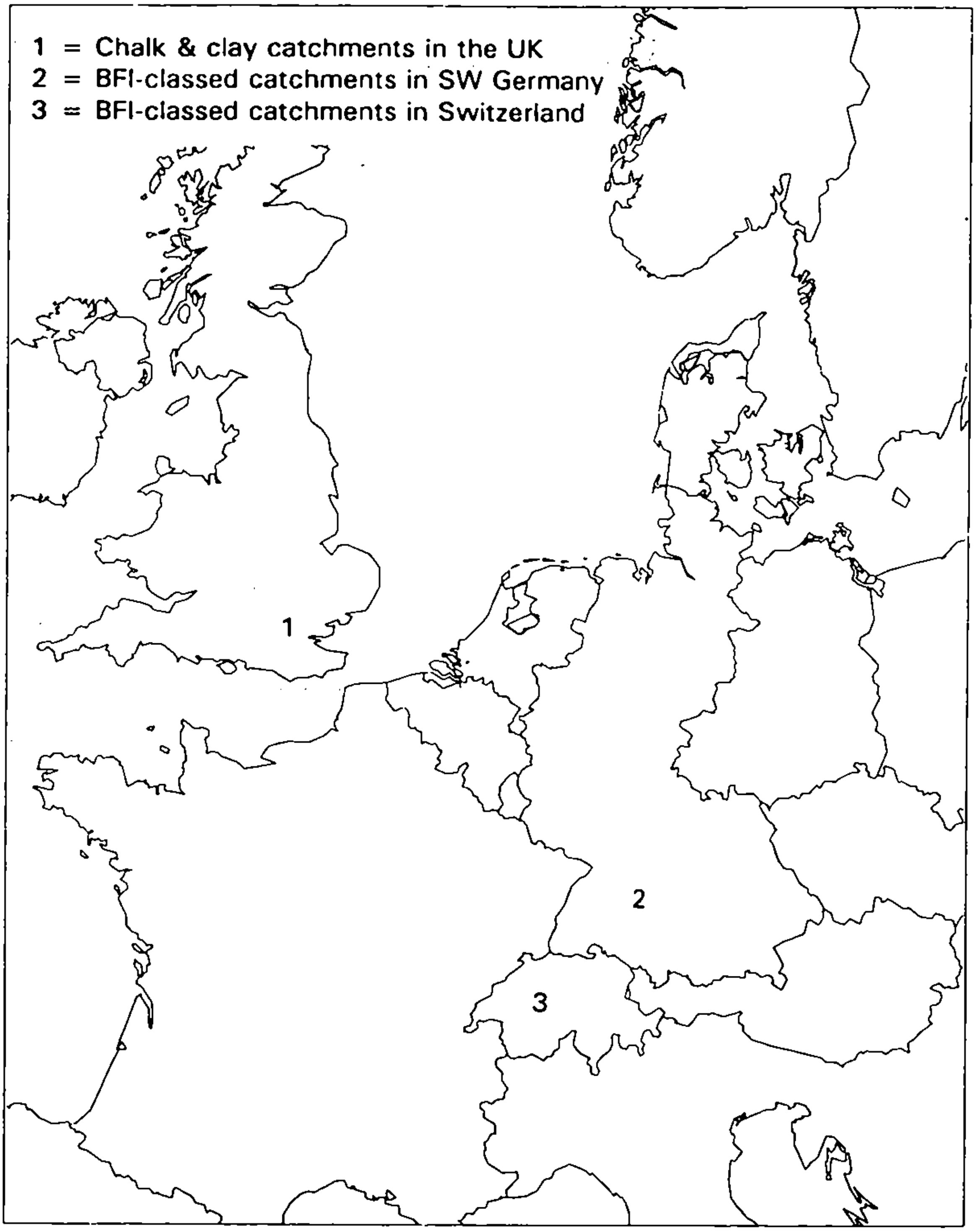

Figure 2.6 *Location of research areas*

3. Results

3.1 Introduction

In the former chapter it has been shown that the results of this study are average storage/yield curves for subsets of gauging stations obtained by applying several selection criteria. The curves represent the probability that a storage will fail on an annual basis to maintain a defined yield to a demand area.

The gauging stations used in this study are stations in the UK, Germany and Switzerland which possess good quality data, as defined by a 'low flow flag' in the European Water Archive (Gustard et al., 1989) with at least 20 years of data.

In this chapter the results are given of the study. In Section 3.2 some general results of the analysis are given, followed by the results of the analysis in the different regions (Section 3.3). In Section 3.4 the results of the study are discussed.

3.2 General results of the application of storage/yield analysis

During the analyses it became clear that the development of deficit volumes does not always occur for all the stations in a sub-set of gauging stations. This effects the results of averaging the storage/yield curves of the different stations. Figure 3.1 shows an example of the effect of a half curve on the position of the average curve. Station 39019 only has points in the probability range < 0.50. Looking at the average curve a shift in the position can be seen for the probabilities > 0.50. It will be clear that only points being the average of all involved stations can be taken into account for the standard curves. This may result in the absence of curves for certain yields and sub-sets. This does not imply deficit volumes do not develop for a certain yield and stations in particular gauging station sub-sets.

3.3 Results of storage/yield analyses for the different regions

3.3.1 The clay and chalk catchments in the UK

The standard storage yield curves for different yields are illustrated in Figure 3.2a and 3.2b for clay and chalk respectively. The solid line shows the part of the standard curve for which all stations in the sub-set contributed. The dashed part of the line is a representation of the presumed way the curve would have been if all stations of the sub-set would contribute. The clay catchment demonstrate a larger range of yields for which failures may occur. The clay catchments have a greater variability of flows with even periods of almost no flow. The chalk catchments conversely show flows which are sustained by base flow resulting in fewer instances where the yield of a reservoir exceeds the inflow to cause failure.

The curves show higher storage volumes are required to sustain a yield in clay catchments than in chalk catchments which is shown in Table 3.1 for a clay catchment (st. no. 39054) and for a chalk catchment (st. no. 39020). For each station and for each yield the three

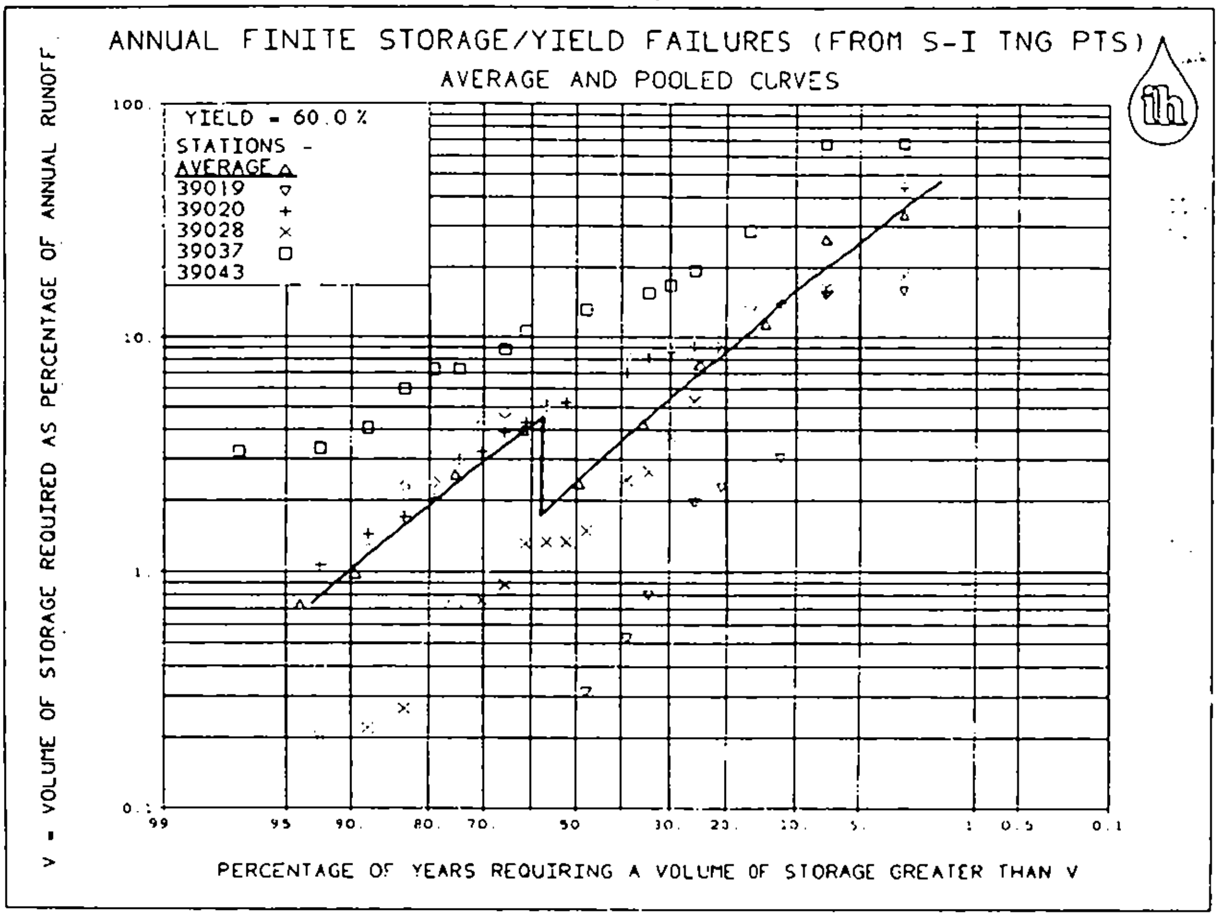

Figure 3.1 *Influence of half curve on average curve*

largest deficit volumes used in the analysis are given.

Table 3.1 *Deficit volumes as percentage of the annual average runoff for a clay and a chalk catchment in the UK for different yields (% mean flow)*

Yield	80%		60%		40%		20%	
	Clay	Chalk	Clay	Chalk	Clay	Chalk	Clay	Chalk
	76	76	48	45	21	18	6.4	1.1
	69	42	38	17	17	17	5.1	-
	43	33	36	15	17	15	5.0	-

The variability if the pooled curves for the chalk catchments and for the clay catchments is demonstrated in Figure 3.3. The clay catchments show a larger variability than the chalk catchments.

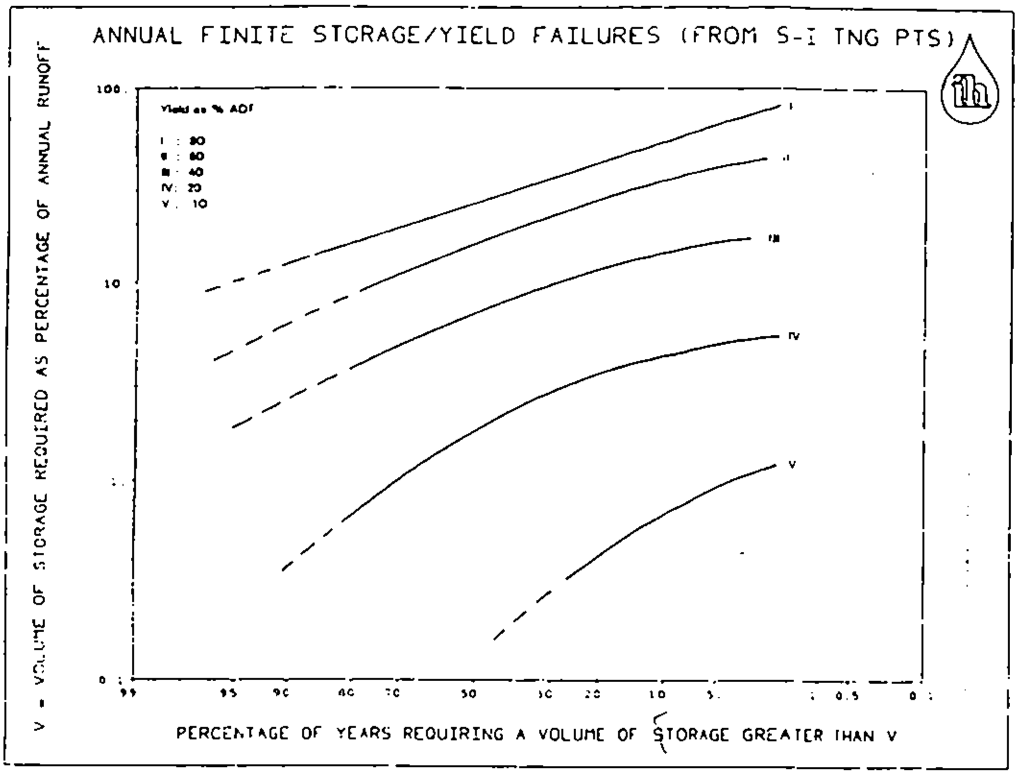

Figure 3.2a *Storage/yield curves of clay catchments in the UK for different yields*

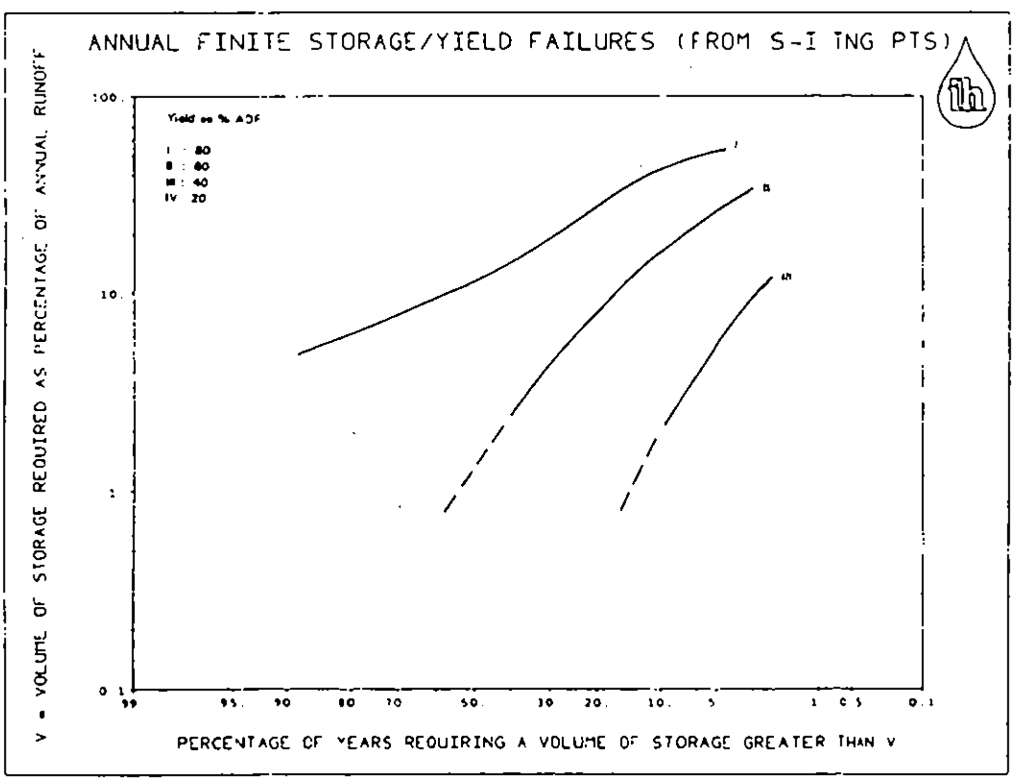

Figure 3.2b *Storage/yield curves of chalk catchments in the UK for different yields*

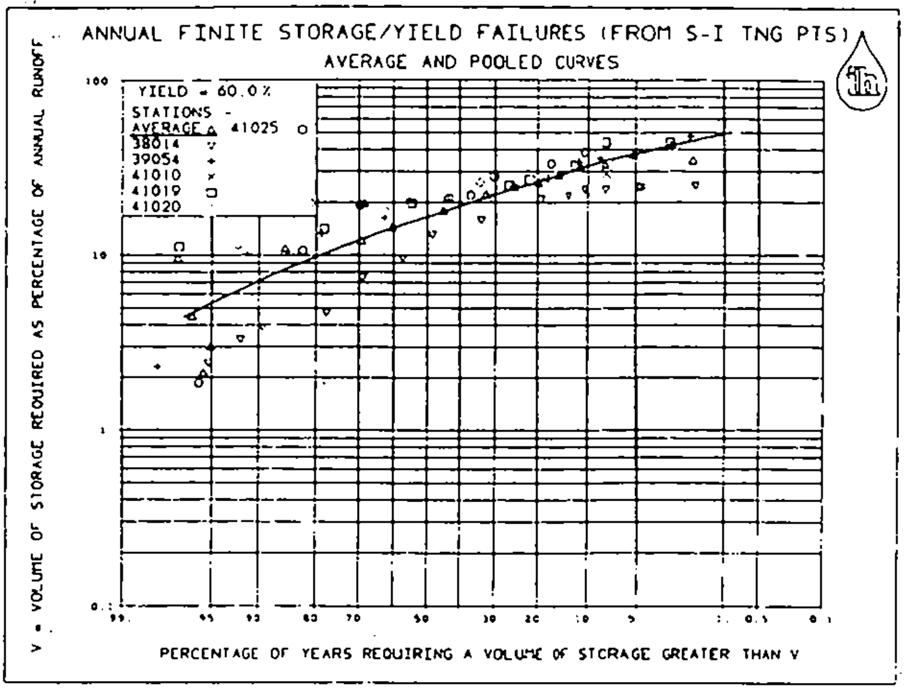

Figure 3.3a *Variability of clay catchment curves used to obtain an average storage/yield curve for clay catchments for a 60% yield.*

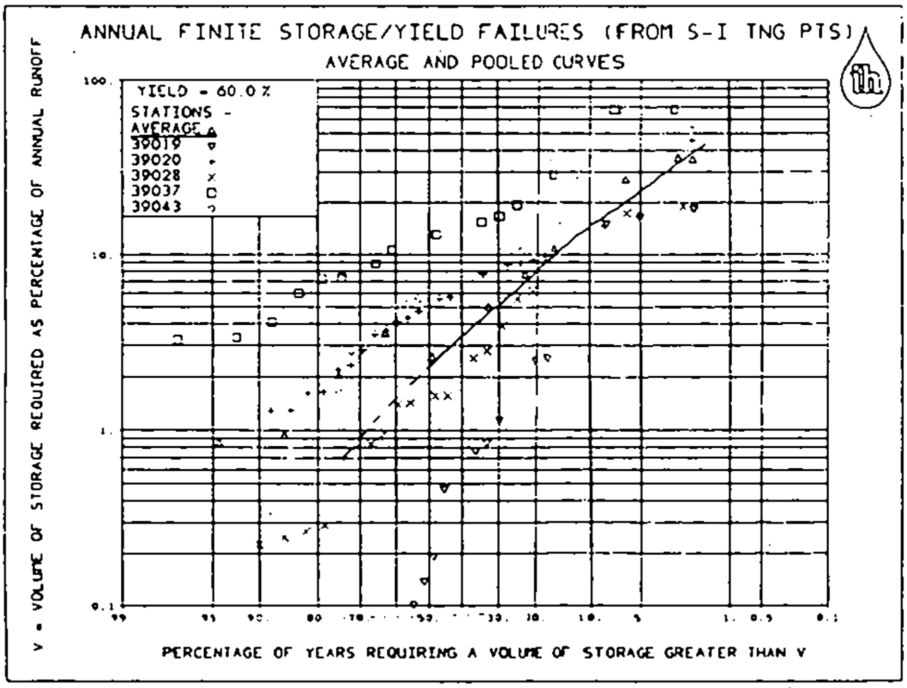

Figure 3.3b *Variability of chalk catchment curves used to obtain an average storage/yield curve for chalk catchments for a 60% yield*

3.3.2 Catchments in Baden-Wurtemberg (Germany) divided over nine BFI-classes

The results of the standard curves in different BFI-classes in SW Germany for 80, 60, 40 and 20% yields are given by Figure 3.4a - 3.4d from which it can be seen that for each yield, catchments with a lower BFI develop larger deficit volumes than catchments with a higher BFI.

In common with the variances of the curves of the chalk and clay catchments to determine an average curve the variance within a group of stations increases with the increase of the BFI.

Not all the BFI-classes are represented in the 20% yield graph. The flow regimes with BFI's above 0.66 which become more permeable and have a higher storage capacity do not all develop deficits bigger than 0.01% of the annual runoff. Averaging the remaining curves would give misleading results.

3.3.3 Catchments in Switzerland with some including mountainous areas

In common with analysis for German stations, storage/yield calculations were undertaken on the basis of BFI-groups. To reduce efforts analyses were performed for the catchments in BFI-range 0.35-0.45 and the BFI-range 0.56-0.65. Figure 3.5a and 3.5b show the position of the curves in comparison with the German curves.

Figure 3.5a shows that for BFI's ranging from 0.36-0.45 bigger storage volumes are needed in Germany to sustain a certain yield than in Switzerland for the higher yields. For the lower yields this difference becomes less clear.

In Figure 3.5b it can be seen that for BFI's ranging from 0.56-0.65 the Swiss curves and German curves almost match each other. The Swiss curve for 20 % yield is not shown because not all Swiss stations in the sub-set of BFI's ranging from 0.56 - 0.65 could be used to calculate the 20 % yield standard curve.

In general the differences between the curves are not pronounced. To get a better understanding of the background of the development of the deficit volumes three German and three Swiss stations were analyzed on the basis of the development of the largest deficits occurring in time. For 40 % and 20 % yields the start date and end date are given of the five largest deficits, used as points in the probability curves, in Table 3.2. The stations used in the table are stations in the BFI-range of 0.36-0.45. If five periods are given in the table it indicates that five or more events took place. If there are less than five deficit dates given for a station and yield it indicates that the exact number of deficits is that given in that section and if no deficit is given at all that for that specific station and that specific yield no deficit has developed during the period of record.

A wide range of start and end dates can be seen. For this range of stations it can be seen that more deficits occurred for the 20 % yield in Germany than in Switzerland. Also Germany has more deficits starting in the summer months than Switzerland. From the dates and especially the years of occurrence it can be seen from the Swiss stations that in Switzerland droughts in the early sixties have major influences on the curves.

Table 3.1 *Start and end date of biggest volume deficits of three Swiss and three German stations for a 20% and 40% yield.*

	Switzerland						Germany					
	St. No. 1621010		St. No. 1621006		St. No. 1621007		St. No. 505040		St. No. 1618050		St. No. 1618053	
	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
40%	Oct 68	Apr 69	Dec 72	Apr 73	Aug 62	Dec 62	Dec 72	Mar 73	Jun 83	Mar 84	Jul 83	Mar 84
	Nov 63	Apr 64	Dec 70	Apr 71	Dec 63	Mar 64	Sept 68	Mar 69	Jul 71	Apr 72	Jul 71	Jul 72
	Sept 71	May 72	Sept 68	Mar 69	Aug 61	Dec 61	Oct 69	Feb 70	Jul 67	Jan 68	Jun 79	Dec 79
	Dec 70	Apr 71	Dec 71	Apr 72	Nov 68	Jan 69	Aug 72	Nov 72	Jul 79	Nov 79	Jan 72	May 72
	Dec 72	Apr 73	Sept 67	Jan 68	Oct 69	Dec 69	Sept 68	Jan 69	Jul 70	May 71	Jan 84	Feb 84
			Aug 69	Feb 70	Dec 71	Apr 72					Jun 76	Jan 77
20%	-	-	Oct 69	Nov 69	Sept 63	Nov 63	Dec 72	Apr 73	Jul 83	Feb 84	Jul 83	Jan 84
			Dec 72	Mar 73			Sept 72	Nov 72	Jul 71	Dec 71	Sept 71	Dec 71
			Oct 68	Jan 69			Nov 68	Mar 69	Aug 69	Dec 69	Sept 72	Nov 72
			Dec 70	Mar 71			Jan 69	Feb 69	Oct 67	Dec 67	Jan 72	Feb 72
			Oct 83	Nov 83			Oct 69	Nov 69	Sept 79	Nov 79	Jul 79	Nov 79
							Jul 76	Aug 76				

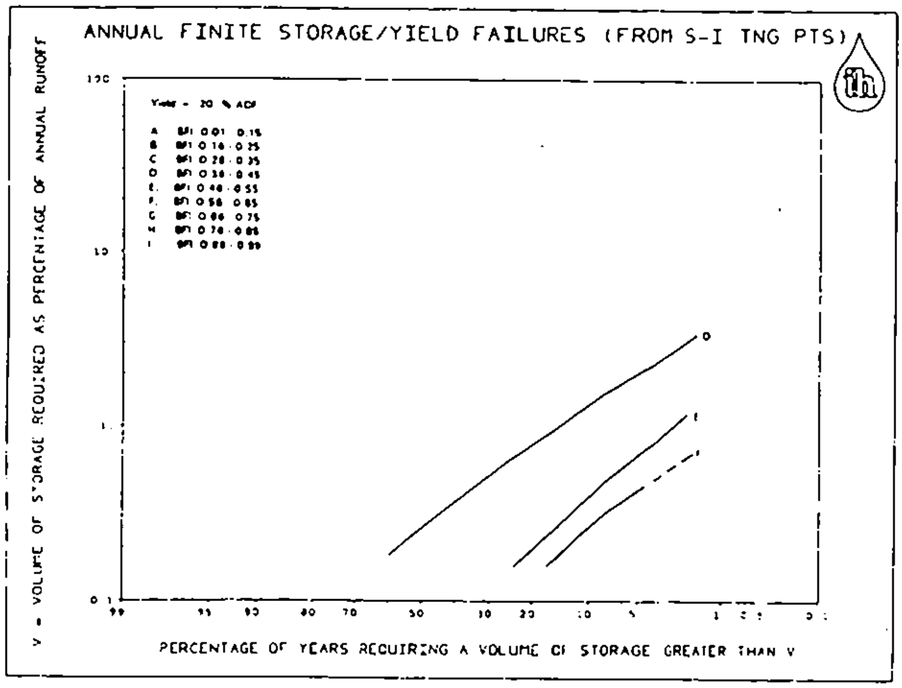

Figure 3.4a *Averaged storage/yield curves of BFI classed SW German catchments for a 20% yield of annual daily flow*

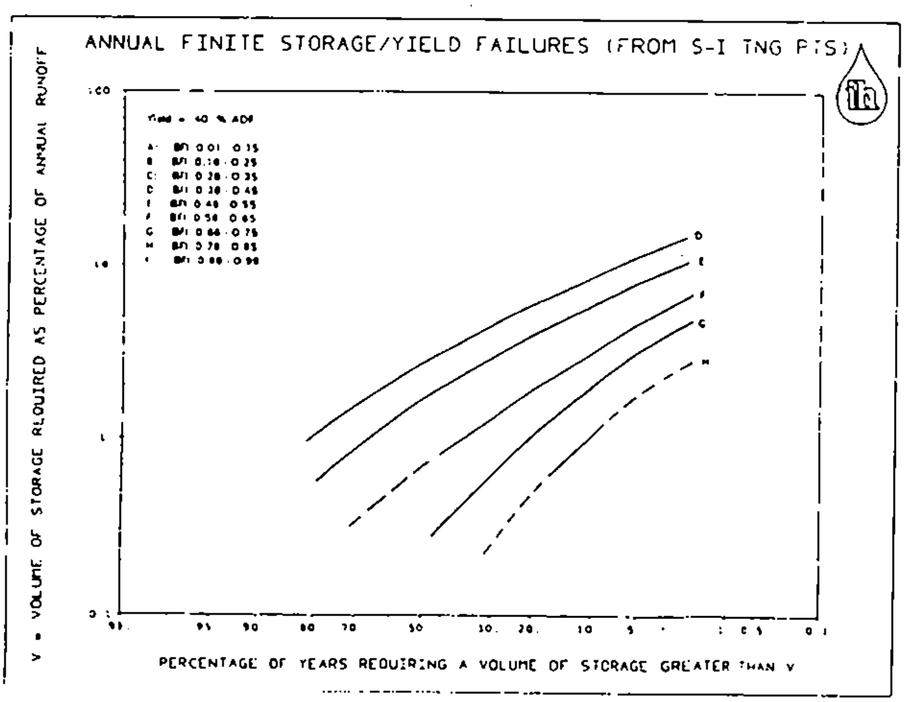

Figure 3.4b *Averaged storage/yield curves of BFI classed SW German catchments for a 40% yield of annual daily flow*

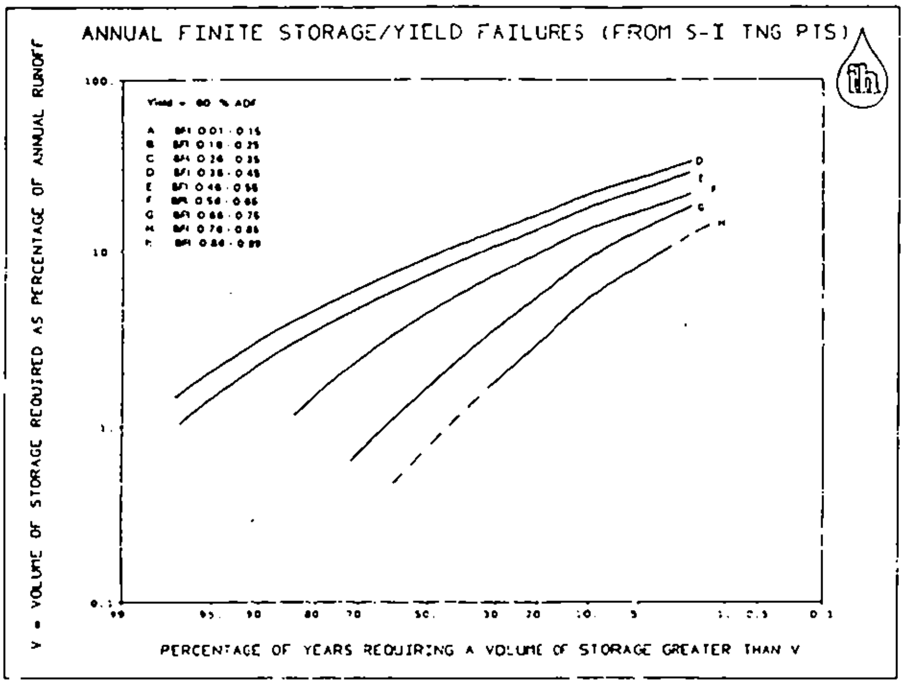

Figure 3.4c *Averaged storage/yield curves of BFI classed SW German catchments for a 60% yield of annual daily flow*

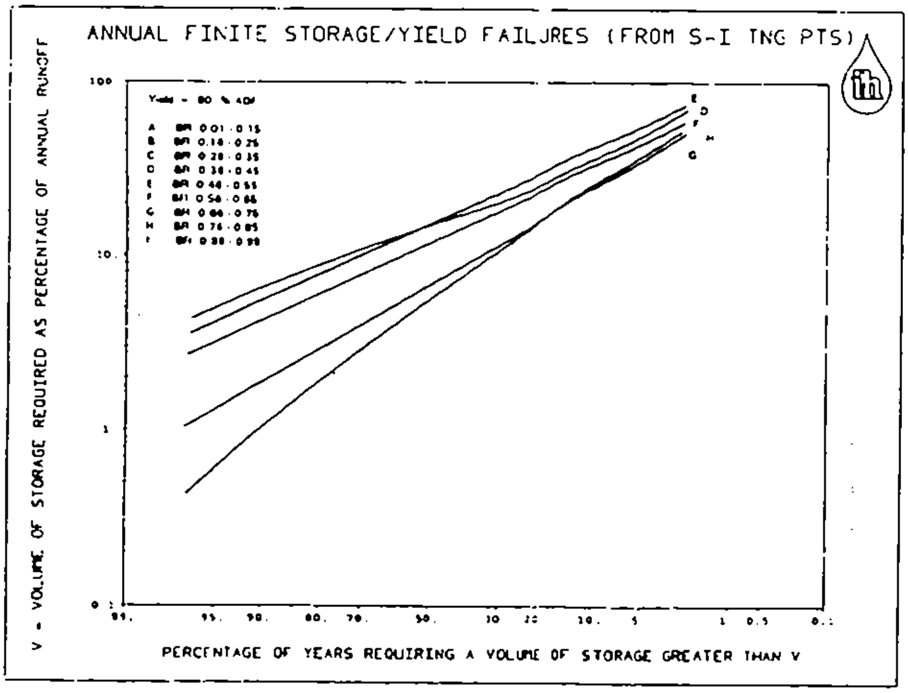

Figure 3.4d *Averaged storage/yield curves of BFI classed SW German catchments for a 80% yield of annual daily flow*

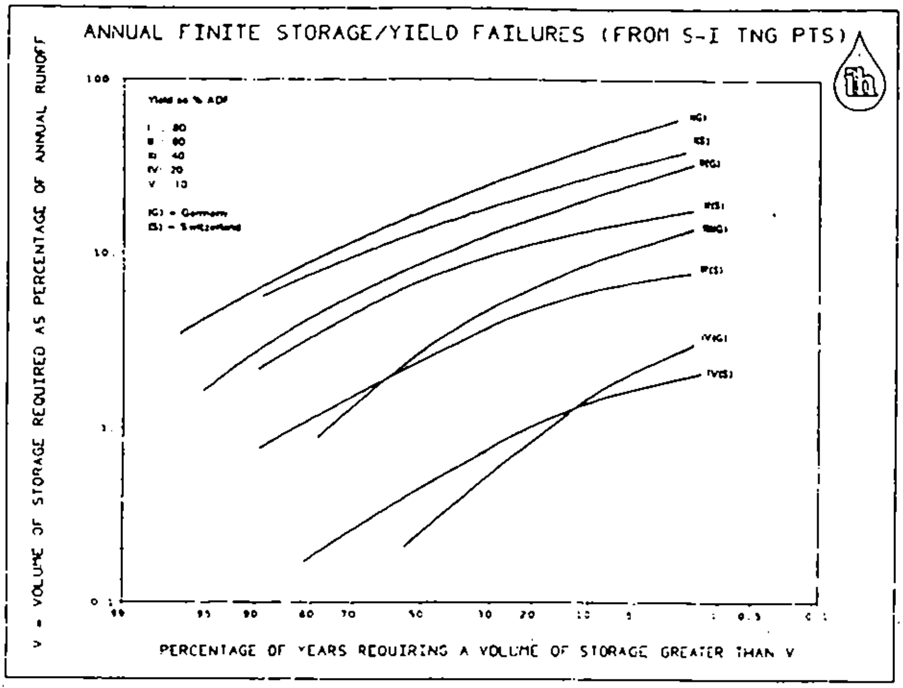

Figure 3.5a *SW German and Swiss averaged storage/yield curves for catchments within BFI-class D (0.36 - 0.45) for several yields*

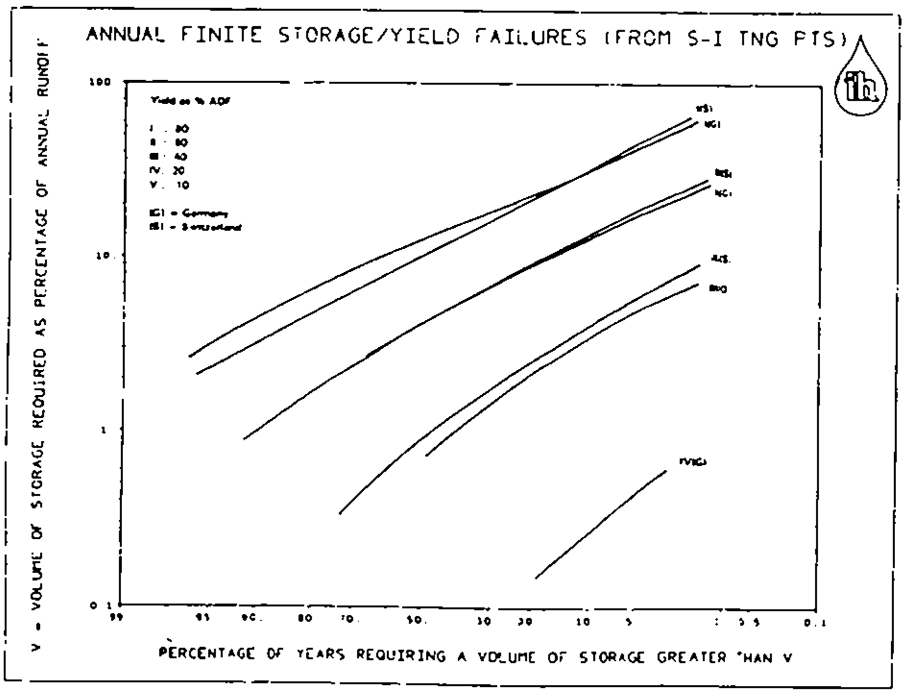

Figure 3.5b *SW German and Swiss averaged storage/yield curves for catchments within BFI-class F (0.56 - 0.65) for several yields*

3.4 Discussion

Section 2.3 identified the requirement for at least twenty years of data to obtain representative storage/yield curves. In this study all the existing data of a station were used to generate the curves. It will be clear that differences in the length of the record have an impact on the storage/yield curves in the sense that the longer the record is the higher the chance it incorporates a bigger deficit volume. Checking the record length against the position of the curves did not give evidence of extraordinary positions of the stations with longer records.

The average curves have been derived by taking the mean of the individual curves for each station in each BFI- or geology class. If few stations are available the question is whether the present stations give a good representation. In this sense the results of averaging few stations should be treated with caution.

The effect of a fixed set of stations is that particular characteristics of these stations are carried over to all the analyses. There is a possibility that a pattern occurring in a group of stations is carried over to all the yields. This may be reflected in similar trends being exhibited for each yield. In particular when comparing results as in the case of those undertaken between Swiss and German stations.

The storage/yield curves show major differences over the different grouped stations, chalk versus clay as well as between the different BFI-classes. The groups with the higher BFI's required less storage to provide a yield than the groups with the lower BFI's. The differences in magnitude of storage requirement are clear. As rivers in dry periods are mainly maintained by base flow the storage/yield curves in the different BFI-classes are believed to be closely linked to the BFI of the catchments and the geology types in the catchments.

As in Table 2.2 has been shown high BFI's are connected to high storage capacity characteristics and high permeabilities and low BFI's are connected to low storage capacity characteristics and low permeabilities in the catchments. The river flows in the chalk catchments are sustained by base flow, causing fewer instances of failure. Therefore the probability of a storage to fail is higher for clay catchments then for chalk catchments. The maintenance of the river flows in the chalk catchments by base flow causes lower storage requirements for these catchments than for clay catchments where the base flow component in the discharge is lower.

The differences between the Swiss and the German storage/yield curves are small. The occurrence or start of the events, as shown in Table 3.2, are not limited to one particular season. The German and Swiss dates show similarities. This could be an indication that the flow regimes have a high grade of similarity and that a simple index such as the BFI enables flow regimes to be categorised.

4 Conclusions and recommendations

4.1 Conclusions

Catchments with a flashy flow regime require a larger storage to provide a certain yield than catchments with a smooth flow regime.

The variability of storage/yield curves in a BFI-class is higher for the higher BFI ranges than the lower BFI ranges.

Storage/yield analysis of river flows shows a clear relation between BFI and storage needed, and assuming BFI is strongly related to the catchment geology and hydrogeology they give evidence of a relation between geology and low flows.

At least twenty years of data are needed to get representative storage/yield curves.

No major differences can be seen in the storage/yield behaviour of catchments in SW Germany and Switzerland, indicating similarities between the flow regimes.

4.2 Recommendations

As a result of the variability in the storage/yield curves being lower in the lower BFI ranges than in the higher BFI ranges the catchments with the lower BFI's are recommended to be used in order to investigate spatial variability of low flows using storage/yield analysis.

If on the other hand the BFI-classification proofs to give standard curves which are the same independent of the chosen flow regime, as for instance given by Arnell et al. (1993), the spatial distribution of the BFI's would already give an insight.

The influence of particular droughts can be investigated over Europe using return periods of storage/yield events. The start and end of an event in time and space can give an insight in the development of droughts over Europe.

It would be interesting to see the storage/yield behaviour of different flow regimes (Arnell et al., 1993) over Europe. It could give an insight in the spatial distribution and availibility of water resources.

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Appendices

Appendix A Base Flow Index

In this appendix a desciption is given for the procedure to calculate the Base Flow Index as it is given by Gustard, et al. (1992).

The Base Flow Index can be seen as the proportion of the river's runoff which comes from stored sources. A computer program applies smoothing and seperation rules to the recorded flow hydrographs from which the index is calculated as the ratio of the flow under the seperated hydrograph to the flow under the total hydrograph (figure A1).

The computer program calculates the minima of five-day non-overlapping consecutive periods and subsequently searches for the turning points in this sequence of minima. The turning points are then connected to obtain the base flow hydrograph which is constrained to equal the observed hydrograph ordinate on any day when the seperated hydrograph exceeds the observed. The procedure for calculating the index is as follows:

1. Divide the mean daily flow data into non-overlapping blocks of five days and calculate the minima for each of these blocks, and let them be called Q_1, Q_2, Q_3......Q_n.

2. Consider in turn (Q_1, Q_2, Q_3), (Q_2, Q_3, Q_4),....(Q_{i-1}, Q_i, Q_{i+1}) etc.. In each case, if 0.9 x central value < outer values, then central value is an ordinate far the baseflow line. Continue this procedure until all the data have been analysed to provide a derived set of baseflow ordinates QB_1, QB_2, QB_3,....QB_n which will have different time periods between them.

3.- By linear interpolation between each QB_i value, estimate each daily value of QB_1...QB_n.

4. If $QB_i > Q_i$ then set $QB_i = Q_i$.

5. Calculate V_B the volume beneath the baseflow line between the first and last baseflow turning points QB_1...QB_n.

6. Calculate V_A the volume beneath the recorded mean daily flows Q_n for the period QB_1...QB_n.

7. The base flow index is then V_B/V_A.

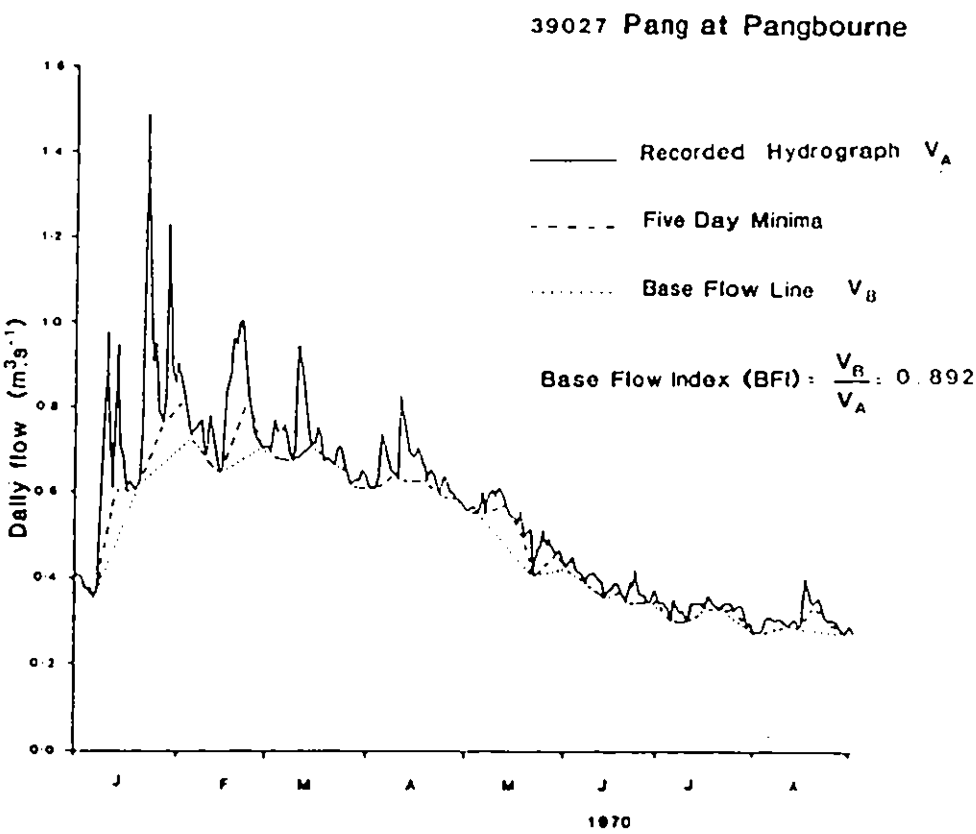
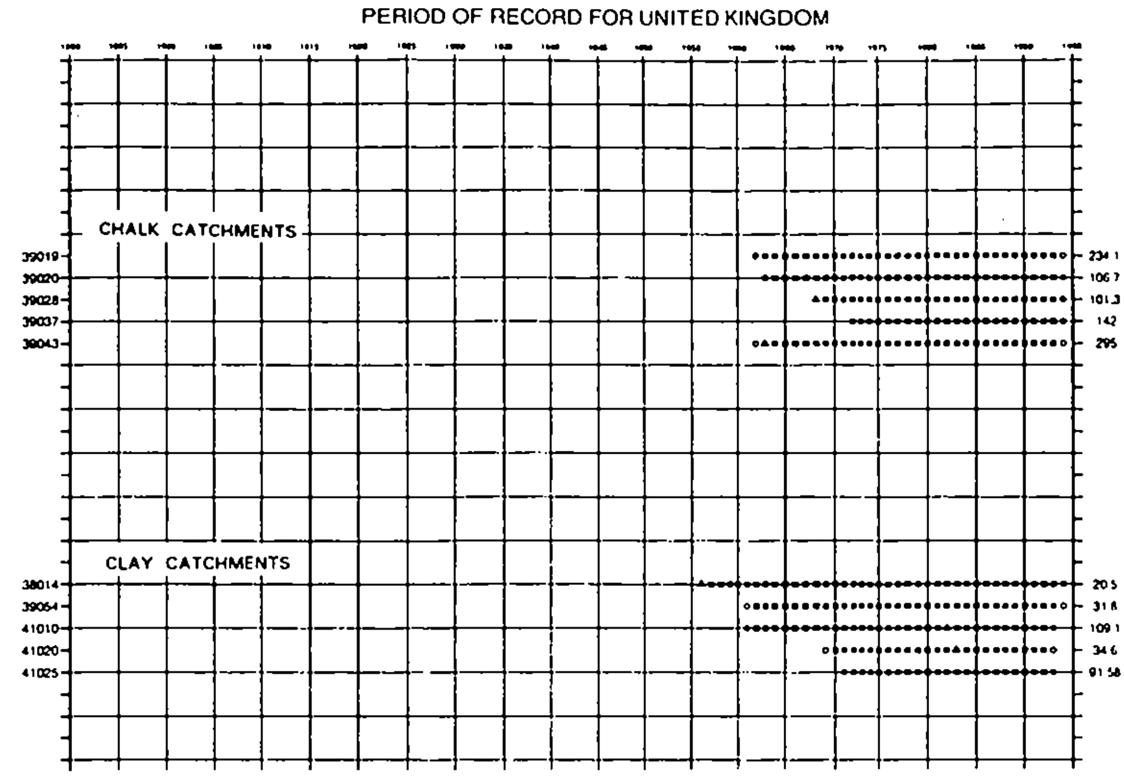
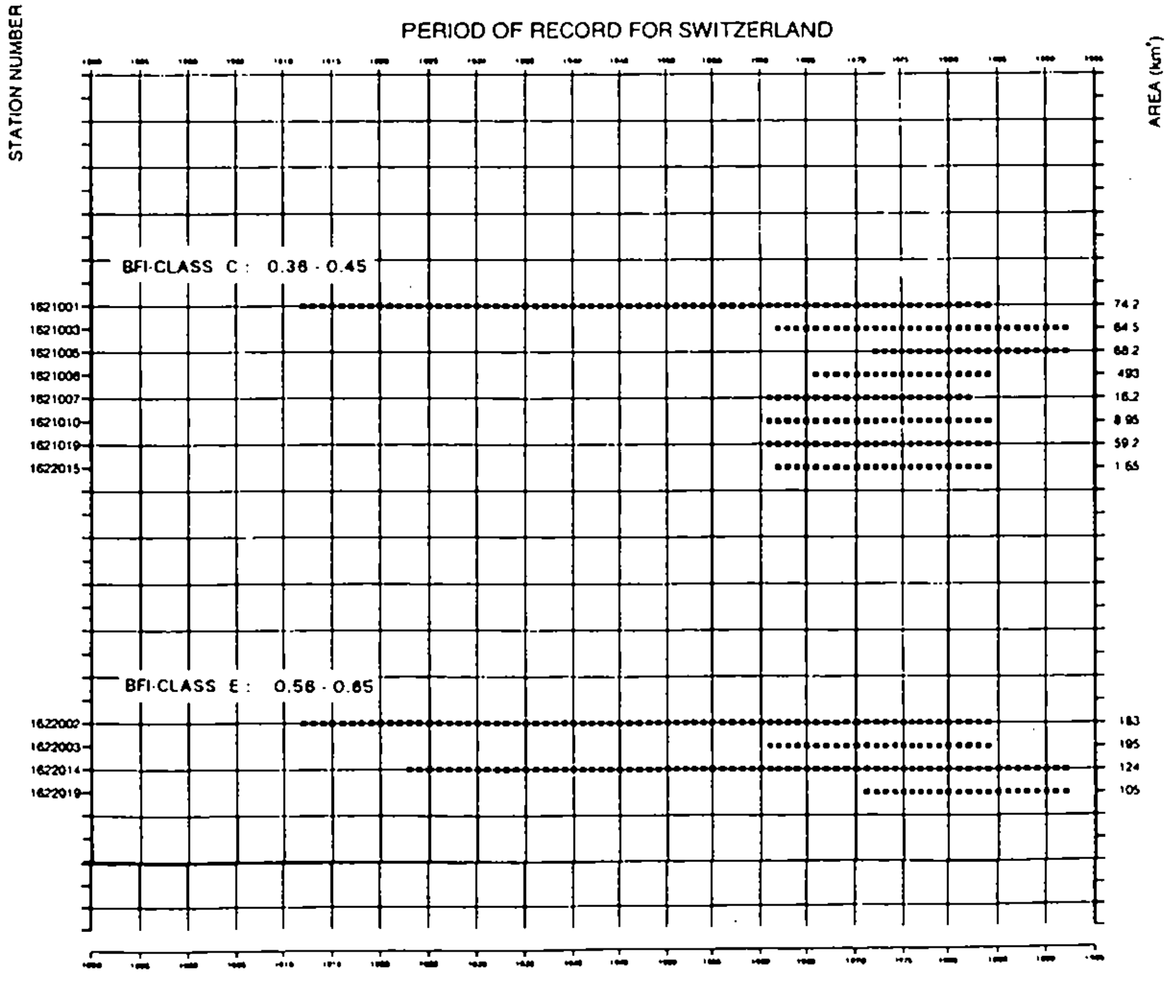


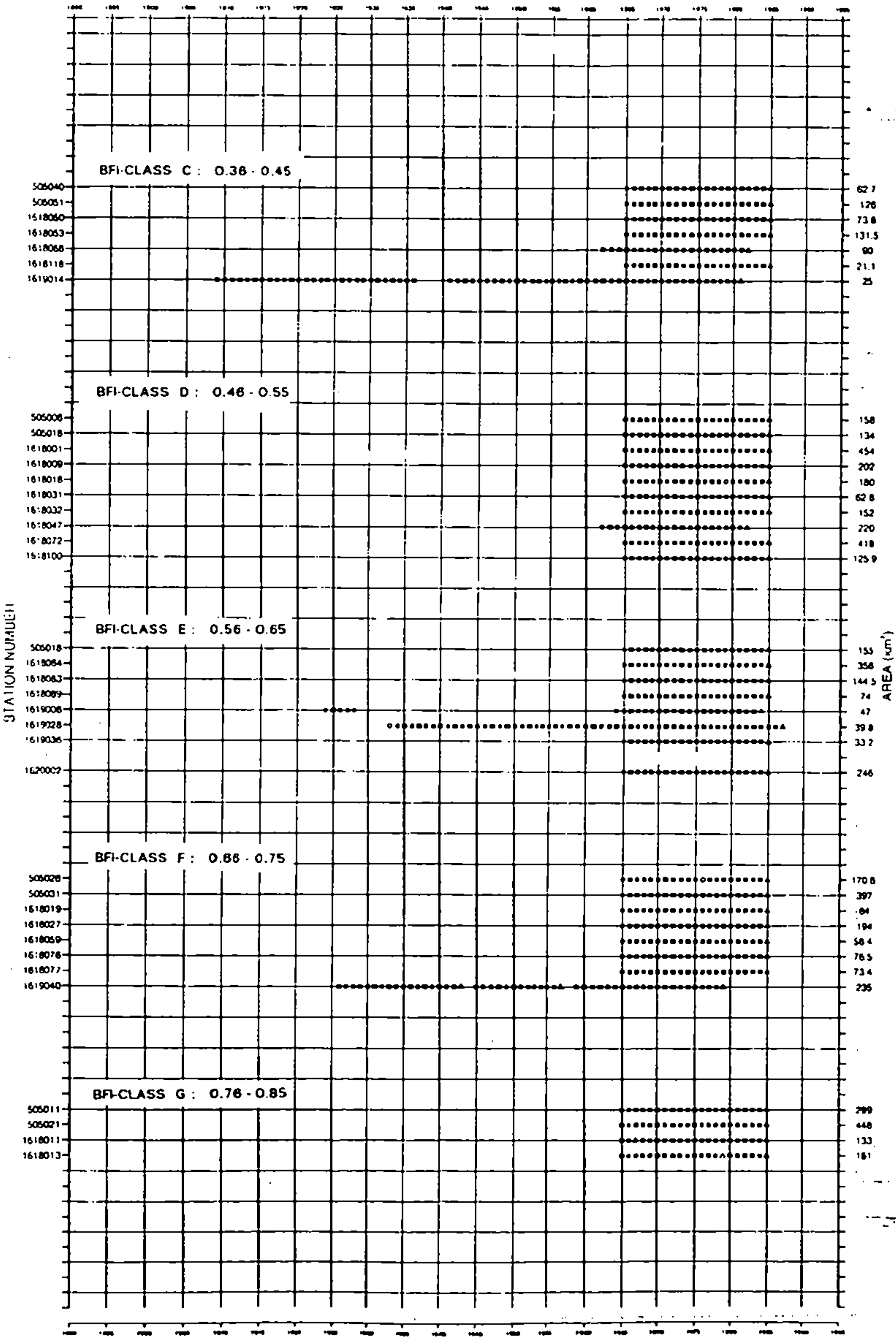
Figure A1 *Derivation of the Base Flow Index (Gustard et al., 1992)*

Appendix B Periods of records of the gauging stations used in the analyses





PERIOD OF RECORD FOR GERMANY



Appendix C Stations and some of their characteristics

In this appendix of each station its number on the European Water Archive, the station name and the country in which the station is situated is given. Htstn represents the altitude at which the gauging is situated and the mean flow is given in cumecs. The base flow is given in % MF and %Mount represents the percentage of area in the catchment above the tree line.

Station number	Station name	Country	Htstn m	Mean flow Cumecs	BFI	% Mount
38014	Salmon Brook at Edmonton	UK	12	.153	.26	
39019	Lambourn at Shaw	UK	76	1.664	.97	
39020	Coln at Bibury	UK	32	1.326	.94	
39028	Dun at Hungerford	UK	99	.718	.95	
39037	Kennett at Marlborough	UK	127	.87	.95	
39043	Kennett at Knighton	UK	105	2.59	.95	
39054	Mole at Gatwick Airport	UK	57	.339	.25	
41010	Adur W Branch at Hatterell Br.	UK	21	.948	.24	
41020	Bevern Stream at Clappers Br.	UK	18	.448	.27	
41025	Loxwood Stream at Drungewick	UK	13	1.040	.22	
505006	Breg at Hammerreissenbach	D	737	5.027	.52	
505011	Lauter at Lauterach	D	517	1.494	.85	
505016	Baera at Fridingen	D	627	1.829	.50	
505018	Schmeie at Unterschmeien	D	582	1.705	.61	
505021	Lauchert at Hitzkofen	D	588	4.502	.84	
505026	Kanzach at Unlingen	D	527	1.189	.75	
505031	Riss at Untersulmetingen	D	702	4.681	.79	
505040	Eschach at Oberhalb Urlau	D	702	2.006	.42	
505051	Eger at Trochtelfingen	D	446	1.393	.44	
1618001	Neckar at Rottweil	D	549	5.178	.50	
1618009	Glatt at Hopfau	D	433	4.473	.51	
1618011	Ammer at Pfaeffingen	D	349	1.151	.83	
1618013	Erms at Riederich	D	321	3.113	.77	
1618018	Murr at Oppenweiler	D	257	2.414	.54	
1618019	Grosse Enz at Lautenhof	D	476	2.199	.73	
1618027	Glems at Unterriexingen	D	198	1.065	.75	
1618031	Fichtenberger Rot at Oberrot	D	370	.965	.51	
1618032	Ohrn at Ohrnberg	D	184	1.655	.54	
1618047	Eschach at Buehlingen	D	570	2.782	.47	
1618050	Eyach at Frommern	D	552	.953	.44	
1618053	Starzel at Rangendingen	D	418	1.366	.50	
1618059	Lauter at Unterlenningen	D	413	1.508	.73	
1618064	Fils at Suessen	D	358	6.111	.59	
1618068	Rems at Hussenhofen	D	343	1.313	.43	
1618072	Rems at Schorndorf	D	247	5.452	.51	
1618076	Bottwar at Steinheim	D	202	.705	.68	
1618077	Kleine Enz at Calmbach	D	408	1.322	.71	
1618083	Waldach at Iselshausen	D	408	1.559	.65	
1618089	Schozach at Talheim	D	192	.587	.65	

Station number	Station name	Country	Htstn m	Mean flow	BFI	% Mount
1618100	Fichtenberger Rot at Mittelrot	D	335	1.798	.55	
1618118	Reiglersbach at Siglershofen	D	421	.234	.44	
1619008	Josbach at Hoelzlebruck	D	833	1.485	.58	
1619014	Menzenschwander Alb,St. Blasien	D	872	1.188	.44	
1619028	Brugga at Oberried	D	460	1.558	.62	
1619036	Bunlott at Buehl	D	138	.814	.56	
1619040	Pfinz at Berghausen	D	122	1.736	.72	
1620002	Schussen at Magenhaus	D	516	2.646	.65	
1621001	Sitter at Appenzell	CH	768	3.603	.42	31.0
1621003	Urnasch at Hundwil	CH	746	2.906	.38	9.0
1621005	Necker at Mogelsberg	CH	605	3.344	.35	2.0
1621006	Thur at Jonschwil	CH	534	21.101	.44	
1621007	Glatt at Herisau	CH	679	.537	.44	
1621010	Eubach at Euthal	CH	900	.411	.36	25.0
1621019	Minster at Euthal	CH	893	3.293	.39	27.0
1622002	Birse at Moutier	CH	519	3.712	.48	
1622003	Suze at Sonceboz	CH	645	4.361	.61	
1622014	Gurbe at Belp	CH	509	2.589	.64	
1622015	Rotenbach at Plaffeien	CH	1275	.091	.37	
1622019	Mentue at Yvonand	CH	927	1.581	.56	